Supply chain management to integrate strategic, tactical and operational planning of wood procurement in the Eastern Cape

By

Pierre Alexander Ackerman

Dissertation presented for the degree of Doctor of Science in Forestry in the Faculty of AgriSciences at Stellenbosch University

Supervisor: Prof R. E. Pulkki

December 2015

Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

This dissertation includes three original papers published in a peer-reviewed journal and one unpublished paper currently under review, for publication, to an accredited scientific journal. The development and writing of the papers (published and unpublished) were the principle responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of the co-authors.
Date: 14 October 2015

Abstract

This study quantifies and models potential monetary gains and improved resource utilisation of a typical forest to mill softwood sawlog supply chain in South Africa through incremental improvements of the various stages of the wood procurement process, given road, silvicultural and management costs. The findings are based on the outcomes of four studies: fibre losses during the timber harvesting phase; establishing a primary transport wander ratio, travel speeds and operations efficiencies; predicting secondary transport travel speeds along with a study of current and potential efficiencies in softwood sawlog transport; and finally a supply chain management case study.

Fibre loss analysed losses occurring in motor-manual and mechanised felling systems, in tree volume above and below 1 m^3, and merchandising at either roadside landing or centralised merchandising yard. Fibre volume losses were categorised according to stump wood, felling and crosscut saw kerfs, log trimming allowance, wood left in field, and excessive trimming and removal of utilisable wood. Total losses ranged from 6.7% and 9.9% of total utilisable volume with stumps generally felled 7 cm higher than necessary. Based on the volume of wood not recovered, the revenue lost was R393 million in board products and R166 million in roundwood supply from plantations annually.

The second study found a wander ratio of 1:1.2. In terms of predicting travel speeds of primary transport, gross power rating (kW), payload size (m^3), extraction distance (m) and slope (%) variables were included. Skidder payloads were found to be approximately 50% of potential design loads.

Truck travel speed predictor variables included Visual Condition Index (VCI), road width, average gradient, percentage of maximum load and truck maximum power. Applying multivariate analysis the predictor variables were reduced to road width and percentage maximum load, and a multiple linear regression equation was produced with an adjusted r^2 of 0.52. Analysis found that overloading of trucks was a common occurrence.

The Case Study required the current forest road network to be repeatedly refined through road decommissioning and selected upgrades over which the timber resource is subsequently flowed to the processing plant. Based on sequentially improved truck speeds, skidder efficiency and fibre use the Net Present Value (NPV) of the various projects, production costs and available timber resource use were quantified. The supply chain was analysed by investigating the effect downstream efficiency improvements have on financial returns over one rotation. NPV results ranged from approximately R40 million to R300 million. The scenario associated with the highest NPV used the most improved road network, highest possible transport speed, and motor-manual felling, cable skidder extraction, merchandising yard and optimal skidder and transport performance. The lowest NPV yielding scenario is associated with an abridged road network, low secondary transport speed, cable skidder extraction, mechanised felling, roadside merchandising, and normal skidder and transport performance. Examination of the individual factors found that

road network; secondary transport speeds and performance had a significant effect. Harvest system had no significant effect.

A limitation of this study was that only the forest to mill supply chain was analysed. Extending the supply chain to the mill and onto the final customer the benefits to the entire chain are expected to increase further. This gap in knowledge is a likely follow-up study.

Opsomming

Die studie bepaal en modelleer die potensiele monitere toename en verbeterde hulpbron gebruik van ‘n tipiese plantasie na meul houtleweringsketting in Suid Afrika deur toenemende verbeterings by die stadiums in die houtaankoop proses, gegewe die pad-, boskultuur- en bestuurskostes. Die studie is gebasseer op die uitkomste van vier afsonderlike studies; veselverlies by houtinoesting, vestiging van ‘n primere vervoer afwykverhouding, vervoerspoed en bedryfsdoeltreffendheid, voorspelling van sekondere vervoerspoed met ,‘n oorsig oor huidige en potensiele doeltreffendheid in rondehout sagtehout saaghout vervoer.Die studie oor veselverlies het die verlies aan vesel tydens masjien-handvel en gemeganiserde velmetodes, vir boomvolume meer en minder as 1 m^3 en verhandeling of op padoorgangsterrein of sentrale verhandelingsterrein. Die verliese in volume vesel is gekategoriseer volgens stomphout, vel en dwarssaag afval, blok (en fout) snytoelating, hout in bos gelaat en die oorsny en oorverwydering van verhandelbare hout. Die totale verliese was tussen 6.69% en 9.86% van die totale bruikbare volume, waar stompe 7cm hoer as nodig gevel is. Die verlies aan inkomste van jaarlikse gelewerde hout van plantasies as gevolg van nie-herwinde hout beloop R166 miljoen in rondehout en R393 miljoen in gesaagde produkte.

In die tweede studie is ‘n afwykverhouding van 1:1.2 gevind. Om vervoerspoed in primere vervoer te voorspel is; bruto krag (kW), loonvraggrootte (m3), veld sleepafstand (m) en helling (%) in berekening gebring. Dit is bevind dat sleeptrekker loonvrag slegs 50% van ontwerploonvrag beloop.Veranderlikes wat vragmotor spoed voorspel, sluit Visual Condition Index (VCI), padwydte, gemiddelde gradient, persentasie van maksimum vrag en maksimum enjinkrag, maar deur middel van ‘n veelvuldige regressie is dit verminder tot slegs padwydte en persentasie van maksimum vrag en ‘n vergelyking met aangepasde r2 van 0.52 is verkry. Die ontleding van vraginligting het bevind dat die oorlading van vragmotors geredelik voorkom. In die laaste studie is die huidige padnetwerk verfyn deur verwydering en opgradering van padseksies waaroor hout na meule vervoer word. Deur opvolgende verbetering in vragmotorspoed, sleeptrekker doeltreffendheid, en verbeterde veselvergebruik is ‘n netto finansiele opbrengs uit die verskillende projekte, produksiekoste en houthulpbron gebruik, verkry. Die leweringsketting is ontleed deur te kyk na die effek wat stoomaf doeltreffendheids verbetering sou he in die opbrengs oor die rotasie gemeet deur ‘n verdiskonteerde kontantvloei ontleding.

Netto huidige waarde (NHW) verkry, het gewissel tussen R40 en R300 miljoen by benadering. Die senario met die hoogste NHW het die mees verbeterde padnetwerk, hoogste vervoerspoed, masjien-hand vel, sleeptrekker uitsleep, verhandelings terrein en optimale sleeptrekker en vervoer perstasie gebruik. Daar is bevind dat die individuele faktore, padnetwerk, sekondere vervoerspoed en prestasie mees beduidend was. Ontginningstelsel was nie beduidend in die studie nie. Die beperking van die studie blyk uit die ontleding van slegs plantasie na meul leweringsketting. Gegewe die huidige resultate, word aanbeveel dat toekomstige studies moet werk aan die uitbreiding na die meul tot verbruiker leweringsketting sodat die voordele vir die totale ketting uitgebrei kan word.

Acknowledgements

I would like to acknowledge the following people and organisations:

- Ms Elizabeth Gleasure.
- Prof Reino Pulkki.
- Prof Daan Nel.
- Di, Simon and Paul Ackerman.
- The South African Forest industry in general and Cape Pine, Merensky and Komatiland Forestry in particular.
- COMPASS FM.
- The UBC exchange students who have been involved in the facets of field work and data collection.

Table of Contents

Figures

Chapter 1: Introduction

With increasing globalisation, the South African forest industry is under constant pressure to improve efficiency, maintain or even enhance wood quality and reduce costs to remain competitive both regionally and internationally with supply chain management being a vehicle to achieve this. The international forest industry has begun to see significant and potential gains coming from improved integration between firms acting as different parts of the supply chain (Carlsson and Rönnqvist 2005, Carle *et al.* 2015). Supply chain management argues that to make the greatest gains in productivity, firms can no longer operate solely as individuals, but rather as entire supply chains focused on the final customer demand and the need to coordinate operations in order to reduce costs and increase optimization across the chain as a whole (Pulkki 2001, Ackerman *et al*. 2015).

The South African forest industry produced R18.5 million^3 of roundwood in 2010 (FSA 2013). Of this, 4.5 million m^3 were softwood sawlogs (FSA 2013). Harvesting and transportation combine to produce the greatest cost component of delivered wood (Pulkki 2001, Abbas *et al.* 2013). Gains in both harvesting and transport efficiency are therefore crucial to reducing overall supply chain costs. Furthermore, reducing other inefficiencies in the supply chain and increasing fibre capture contributes to improved revenue and the utilisation of the overall fibre resource in South Africa (Ackerman and Pulkki 2012, Ackerman *et al.* 2014, Ackerman *et al*. 2015). Given the importance of softwood roundwood to the South African forestry industry, a supply chain model was developed for the Eastern Cape forestry region, a significant contributor to country's softwood sawtimber industry (FSA 2013).

The goal of the studies that went into producing the supply chain model was to ascertain where inefficiencies in the softwood sawlog supply chain lie and how to best mitigate these factors in order to reduce total value chain costs and improve fibre utilisation. Although the principles of supply chain management emphasise the integration of the complete (forest to final customer) value chain, this work is limited to the first phase of the chain: forest to mill. Paper I (Ackerman and Pulkki 2012) examines fibre losses across two felling methods, two primary transport systems, various tree sizes and merchandising locations. Paper II (Ackerman *et al.* 2014) examines two skidder-based primary transport extraction systems and determines a wander ratio, travel speeds and primary transport productivity. Paper III (Ackerman *et al.* 2015) examines softwood sawlogs secondary transport in terms of road surface conditions, various road classes, payloads and the resultant effect on truck travel speeds. Based on the results of these studies, the most efficient situation for each context (fibre loss, skidder-based primary transport and secondary truck transport) was determined. However, individual enterprise optimisation, when examined on a supply chain level, may actually result in sub-optimal results at the chain level (Pulkki 2001, Carle *et al*. 2015). To bring the three studies into perspective, Paper IV developed a supply chain model which examines the interactions of potential interventions at individual levels of an enterprise's supply chain, with the outcome determining which of the interventions would result in the most beneficial use of the resource and value potentially gained, based on discounted cash-flow theory over an average pine plantation's rotation of 30 years, annually.

Hence the objective of this study is to quantify and model potential monetary gains and improved resource utilisation of a typical forest to mill softwood sawlog supply chain in South Africa through incremental optimisation of various stages of the wood procurement process, given the additional silvicultural and management costs.

The Appendix contains a declaration, declaring the nature and extent of the main authors' contribution to the work done in both the individual papers and this dissertation. It also contains the names of co-authors and the nature and extent of their contributions in individual papers.

Following this introduction is a background section, which is designed to give the reader an understanding of supply chain management, how supply chain management has been applied to forestry, and finally, an introduction of the modelling technique used in this study.

Chapter 2:

2.1 Supply Chain Management

Supply chain management is a business concept that has been used by internationally competing firms such as Kimberly-Clark and IBM to achieve competitive advantages (Poirier 1999). The supply chain itself can be defined as "…a network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer" (Christopher 1998). While commonly referred to as supply chain management, synonyms include logistical management, total systems costing, holistic approach and total production management (Pulkki 2001). Supply chain management which has evolved into the modern day value chain optimisation concept is viewed as much of a supply chain management strategy as a way to further manage the industry's capacity to lower resistance to change (Carle *et al.* 2015).

As companies have worked to concentrate their businesses on their strongest activities, other activities required in support of these prime activities have been outsourced to other firms, who in turn are superior at this outsourced activity. As a result, to optimise and gain greater competitive advantage, be it through increased market share, cost reduction, and improved quality and inventory management, firms have to work together to optimise the entire supply chain (Stadtler and Kilger 2005). Firms can no longer focus on processes under their individual firm's control, instead the entirety of processes cumulating into the final product need to be considered (Carle *et al.* 2015). Indeed, it has been proposed that in the future complete supply chains will compete rather than individual firms (Poirier 1999).

Typically in the past, supplier and downstream customer relationships were distanced if not outright adversarial and a Darwinian idea of the better firm surviving dominated (Christopher 1998). Supply chain management therefore requires a different approach where paradoxically the firms that work together do better (Christopher 1998). Sub-optimisation within the chain is no longer valid, as gains made at a lower level may become non-existent or even detrimental at the supply chain level (Pulkki 2001, Carle *et al.* 2015). Supply chain management therefore requires management of inter-firm relationships in order to achieve a more profitable outcome for all (Christopher 1998). Furthermore and in reality the end customer should also be incorporated as part of the supply chain (Stadtler and Kilger 2005, Carle *et al.* 2015); firms higher up the chain should focus on the end customer demand and needs. A schematic example of a supply chain can be seen in Figure 1.

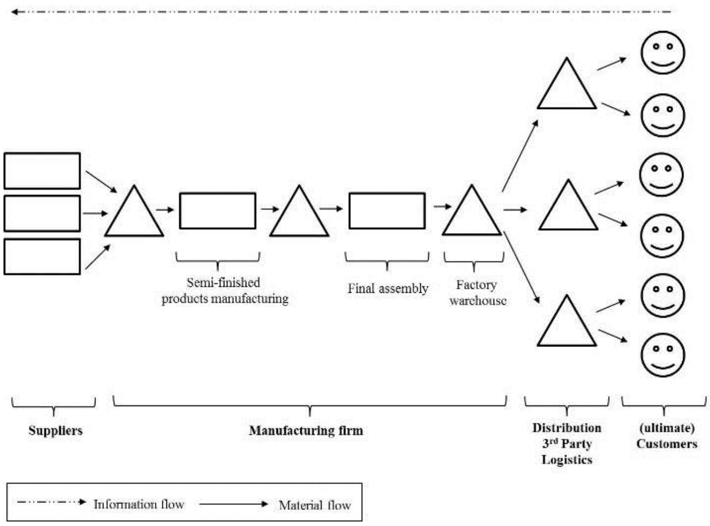

Figure 1: Example of a supply chain (Stadtler and Kilger 2005).

2.2 Supply Chain Management and the Forest Industry

The forest supply chain is unique when compared to other industries (Chauhan *et al.* 2009). Firstly, forest supply chains are divergent (Frayet *et al.* 2007, Carle *et al.* 2015). Wood fibre produced from forests flows down the supply chain, undergoing a number of form changes, to a diverse array of products from traditional lumber to pulp and chemical products such as medical cellulose and even biomass for energy. Steps made at each level of the chain can therefore reduce or increase the fibre available and its value for subsequent steps (Carle *et al.* 2015). Wood fibre itself is also a heterogeneous product (Frayet *et al*. 2007), varying depending on many factors, including species, with different fibre attributes suitable for different end products. To make the supply chain even more complex, the wide distribution of the growing locations place considerable strain on infrastructure and infrastructure development. The wide array of different products and products at intermediate stages of the value chain does not allow for a one-fits-all logistical solution.

Due to the complexity of obtaining wood fibre and then converting it to an end product, the forest supply chain is also characterized by multiple firms (Lintu 1986). The risk of sub optimisation is therefore high as each firm naturally focuses on its own end gain. Although for an individual firm, strategies may prove effective, ultimately sub-optimisation hinders the entire chain. Understanding the entirety of the chain and synchronising chain activities is required to capture the full value of market opportunities and improve sustainability of the chain long term (Carle *et al.* 2015)

Logistics in the forest supply chain are complex due to the unique actions and requirements along any particular value chain. Simplistically put, the standing tree's form is changed through felling and subsequent processing. The tree or its parts are then relocated to a suitable location for loading and transportation of assortments to a mill. At the mill the tree or its parts are converted to products and these products are then transported to various customers. This complexity results in harvesting and transportation costs accounting for 60-70% of the total delivered wood cost (Pulkki 2001).

These challenges make the forest supply chain unique, but also highlight the need to examine it in more detail, albeit in this work on the individual enterprise and only from forest to mill; this provides a unique opportunity for the South African forest industry. A properly managed forest supply chain should look at optimising the wood/fibre yield, wood/fibre quality and production costs across all firms (Pulkki 2001, Carle *et al.* 2015) to get the most value.

Supply chain management has been examined in forestry in terms of certification (Rotherham 1999; Lawrence 2007), decision support (Epstein *et al*. 1999; Carlsson and Rönnqvist 2005), sustainability (Berg *et al*. 2012) and, particularly in the last five years, biomass and bioenergy (Frombo *et a*l. 2009, Conrad IV *et al*. 2010, Windisch *et al*. 2010, Gold and Suering 2011, Abbas *et al*. 2013).

Decision making across the supply chain can occur at several levels, from the highest strategizing involving governments and industry leaders to tactical planning to day-to-day operational planning (Carle *et al.* 2015) (Figure 2). This study focuses on the intermediate level of optimal forest and asset management. Planning at this level involves examining the business model and supply chain capabilities through optimising the road network design and plantation access, transportation, harvest methods, and merchandising location among others (Carle *et al.* 2015).

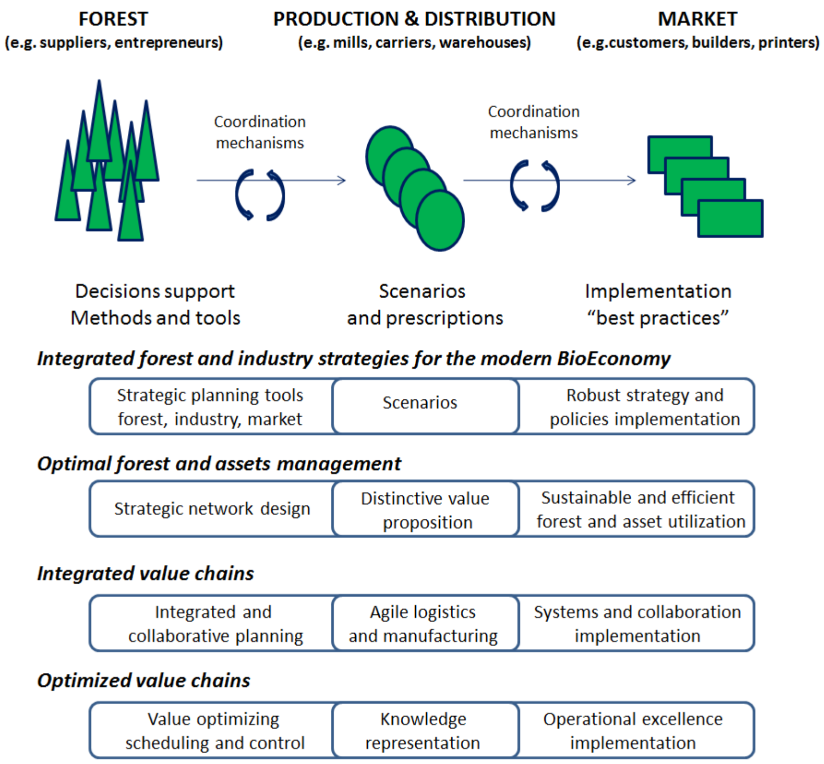

Figure 2: Levels of planning which occur across the forest supply chain (Carle *et al*. 2015).

2.3 Softwood sawtimber supply chains in South Africa

Most of softwood sawlog supply and processing in South Africa is in the hands of three major players (FSA 2013), who largely supply their own processing plants with raw material from within

South Africa. They are mostly vertically integrated with only the secondary transport phase partially outsourced. In the recent past, the timber harvesting phase was also outsourced, but this is now, particularly for ground skidding harvesting operations, under the control of the parent company. The reason for insourcing this phase was to be able to exercise greater control of cost and production which was not easily possible with outsourced work as being experienced in South Africa at the time (Ackerman and Laengin 2010).

Softwood sawlog clearfell harvesting in South Africa has largely, and traditionally, been done utilising semi-mechanised full-tree and tree-length cable or grapple skidder extraction systems to roadside (Ackerman and Laengin 2010). In contrast, thinnings, due to space restriction in the stand, have been motor-manually felled within a cut-to-length system and extracted either with animals or mechanically using small agricultural tractors fitted with A-frames or single/double drum winches (Ackerman and Laengin 2010). Relative to clearfelling, the lower volumes emanating from thinnings have limited the potential development of thinning specific mechanised harvesting systems (Ackerman and Laengin 2010).

On the whole, in South Africa, felling is predominantly motor-manual with tree-lengths being extracted via cable skidder. However mechanised systems, such as drive-to-tree feller-bunchers coupled with potentially higher production grapple skidders, are becoming more common (Ackerman and Laengin 2010). Debranching is done motor-manually at either stump with motor-manual felling and cable skidder extraction, or at roadside landing following mechanised felling and grapple skidder extraction. Merchandising, which includes log-scaling and cross-cutting, is completed at either roadside or at a merchandising yard, which is located at the processing plant depending on the system in use (Ackerman *et al.* 2010). Merchandising is done motor-manually.

Mill-based merchandising yards in South Africa have reduced in number from four in the late 2000's to one currently. The reason for this reduction is that the potential gain predicted through product diversification, potential cost reduction due to centralised locations and increased revenues was never realised at the time (Ackerman and Laengin 2010). It was envisaged that tighter control, particularly for optimised assortment production, would be greater than with roadside merchandising, but in fact the challenges experienced with roadside merchandising were instead merely transferred to the new location – indicating largely a human induced problem (Ackerman and Pulkki 2012).

A second challenge facing centralised merchandising was that, due to the potentially higher production rate of the feller-buncher/grapple skidder full-tree systems, specialisation was necessary as the system would work across a number of estates to achieve the full potential gain. Due to the rapidly advancing operations, infrastructure improvements to cater for specialised tree-length transport systems could not keep pace. In addition the high intensity merchandising yard activities (decking, scaling, crosscutting, sorting and log assortment recording), all in the confined space of the merchandising yard, were never really mastered and aspects such as residue management amongst others continually challenged the operation (Ackerman and Laengin 2010).

In terms of applying supply chain principles to the softwood sawlog value chain, there is not much being done in South Africa as is shown in the complete lack of relevant literature on the subject. What is evident, as with the pulpwood industry is that structural mill processing is still distinctly separate from forest operations, and ownership of wood changes at the mill gate or even at roadside landing. Processing decisions are made by the mill and wood procurement decisions are made by the forest enterprise, with no recognition of the potential gains that can be achieved by understanding the impact of decisions and efficiencies either upstream or downstream in the value chain.

This study is unique in that it is the first of its kind to examine any form of the softwood sawlog value chain in South Africa, albeit from the standing tree to in-feed chain at the processing plant rather than from forest to final customer purchasing the product from the mill.

Southern Forests 2012, 74(2): 133–149
Printed in South Africa — All rights reserved

SOUTHERN FORESTS
ISSN 2070-2620 EISSN 2070-2639
http://dx.doi.org/10.2989/20702620.2012.701412

Chapter 3: Fibre volume losses of eight softwood clearfell harvesting systems in South Africa

P Ackerman[1*] and R Pulkki[1,2]

[1] *Department of Forest and Wood Science, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*
[2] *Faculty of Natural Resources Management, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada*
** Corresponding author, e-mail: packer@sun.ac.za*

A study of both fibre volume loss and related opportunity cost was performed across the South African softwood sawtimber industry to gain information on the actual utilisation of useful fibre and potential loss or gain of opportunity in terms of potential revenue from both field practices and policy. The study quantified volume losses from high stumps, felling and crosscut saw kerf, log allowances, excessive removal of merchantable wood, incorrect log trimming allocation, and utilisable wood left in-field. Eight treatments were examined: four terminated with merchandising at roadside landing and four at merchandising yards. Within the treatments, felling was either motor-manual or mechanised and compartments were classed by average compartment tree size (less than or greater than 1 m^3). Total wood utilisation was found to be 92.07%. Stumps were found to be 7 cm higher than necessary and volume losses because of high stumps were 0.79% and 0.07% for mechanical and motor-manual felling, respectively. For felling saw kerf losses, mechanical felling showed 0.92% loss, whereas motor-manual felling resulted in only 0.15% loss. Incorrect log trimming allowance provided for 0.60% loss. Excessive trimming of logs resulted in 2.02% loss. Volume lost because of crosscutting saw kerf was low at 0.20%, but tops not being extracted resulted in 2.57% loss. Using SIMSAW 6 simulations, these volume losses translated into an additional annual harvested volume of 421 722 m^3 or additional 1 278 ha harvested area, R166 million log value and R393 million net lumber value loss. Total loss was lowest (6.49%) in the average tree size class less than 1 m^3, which was mechanically felled regardless of merchandising location. For the majority of volume loss categories, motor-manual felling caused greater loss when compared to mechanical felling methods. Log trimming allowance consumed 80 604 m^3 annually. The results indicate that the human element may have a greater impact on fibre and value losses than the system choice. Further research is recommended to quantify the effect of the human element.

Keywords: economic analysis, fibre loss, log allowance, mechanisation, merchandising, timber harvesting

Introduction

Study context

The South African forest industry harvests approximately 23.0 million m^3 of roundwood annually, of which about 4.7 to 5.0 million m^3 is saw timber and veneer logs valued at R1 700 million (FSA 2009). In order to harvest the 23.0 million m^3 and make it available to industry for processing, about 76 000 skilled and semi-skilled people are employed and an array of tools and equipment used, which range from basic hand tools to sophisticated machines (FSA 2009). Although some of this volume is harvested by company-employed personnel, mostly in saw timber operations, a significant portion of the roundwood pulpwood volume is harvested by contractors. The human resources employed require training and support to ensure the sustainable delivery of high-quality products. During harvesting operations, losses occur when available merchantable tree volume (veneer, sawlogs and pulp/chip logs) does not reach a predetermined processing installation or is damaged along the supply chain. For sustainable and effective harvesting operations, these losses and damages must be minimised through correct harvesting systems and practices.

In a review of the literature it was found that considerable work has been done internationally to understand and quantify fibre losses during the harvesting process. However, the literature varies in content and results are often conflicting. This is mainly because the studies are focused on individual operations that may vary considerably in regard to level of worker training and commitment to sustainable timber harvesting practices, working conditions, and planning and implementation. In the present study fibre losses refer to actual volume losses, as well as damage to stems/logs that influences volume and value recovery.

Fibre losses

A number of factors contribute to fibre loss and thus value recovery in harvesting and transport operations. These losses include (Araki 1996, Favreau 1997):

- high stumps and wide saw kerfs
- improper felling resulting in: stem breakage during felling and on-ground or through-obstacle impact; and poor cuts, stem splits, barber chairs and pulled fibres
- damage and/or breakage from excessive or rough handling by extraction and loading equipment

- merchantable trees left standing or felled trees left behind in the clearfelling compartment
- inaccurate log crosscutting lengths and subsequent merchandising
- inefficient processing of logs in the mill.

Murphy et al. (1991) and Murphy (2003) observed losses in harvesting because of excessive or rough handling, including felling breakage and damage, extraction breakage, crosscutting damage, and loading/unloading damage. Favreau (1997) found that more breakage and fibre loss occurred in full-tree (FT) harvesting (10%) than in cut-to-length (CTL) operations (1%). The damage during FT operations generally occurs when skidders travel over decked full-trees. Fibre losses also occurred because of loader grapple damage to stems during loading (Favreau 1997). A study by FERIC (2004) found that fibre loss because of skidding and delimbing amounted to 7% of total available volume. FERIC (2004) found that delimbing stems as soon as they arrive at the roadside and ensuring there is never more than one skidder load at the roadside at a time reduced stem breakage by 7%. Hot logging avoids stem breakage because of the skidder driving on piles, pushing trees into the pile and intercrossing the stems within the pile (FERIC 2004). Gingras (1992) found that mechanical FT logging with roadside delimbing-debarking-chipping had both high productivity and a fibre recovery ratio of 99%. Felling timber to lead (orientating tree lengths, either butt- or top-end to the direction of extraction), to avoid stems being swung at sharp angles was also found to be effective in reducing breakage during log extraction (Murphy et al. 1991).

According to Gingras (1992), motor-manual felling results in less fibre loss because the trees are felled on an individual basis and the chance of stems being left in the compartment is decreased. Favreau (1997) found that fibre losses occurred during fast, stop-start operations of the feller-buncher and when the operator had to make rapid decisions regarding which stems to cut when a minimum diameter had to be observed. Gingras (1992) also found that using mechanical CTL with a harvester/forwarder combination improved fibre yield. This is supported by Ride (1999) who found that CTL produced higher efficiency in fibre recovery (87.4%) than tree-length (TL) harvesting (82.1%) and FT harvesting (77.0%); all were fully mechanised systems.

In a separate study Gingras (1992) also found that fibre losses did occur during mechanical CTL harvesting operations where entire piles of unprocessed trees were found under the slash during postharvest assessments. The same incidence of lost fibre of up to 40.0 m^3 ha^{-1} were found under windrowed branches and bark in South African motor-manual clearfell *Eucalyptus* pulpwood harvesting compartments (Bilborough 2008). Favreau (1997) found losses from overlooked felled and processed stems in the cut-block along with stems overlooked at the bottom of delimbing piles as a result of being covered by snow or frozen to the ground.

Murphy and Olsen (1988) found that the best way to minimise fibre loss was to improve the decisions made during motor-manual log crosscutting by adjusting the location of merchandising. The percentage of log volume that did not meet specifications was higher when logs were crosscut at the stump than at the landing (30% vs 20%) because of several factors that hinder the crosscutter's judgment at the stump (e.g. brush and vegetation) on steeper slopes. This resulted in the crosscutting point being chosen more by efficiency or safety instead of the product dimensions (Murphy and Olsen 1988).

Young (1998) and Carey and Murphy (2005) found that mechanical harvesting systems had problems maximising prime lengths (preferred log lengths designated by a company that allow for the most flexibility for log utilisation in the mill), and in identifying stem form or defects in small-diameter trees that eventually result in fibre and value loss. However, mechanised systems generally have a higher productivity than motor-manual systems (Carey and Murphy 2005). Murphy et al. (1991) found that the majority of fibre loss was the result of management's choice of log grades, as opposed to log grades cut by the log-makers that did not meet specifications and had to be rejected.

With regard to semimechanised and mechanical tree-length harvesting of softwood saw timber in South Africa, much of the literature available suggests the factors contributing to a large portion of fibre and value loss are high stumps and wide saw kerfs (Murphy and Olsen 1988, Warkotsch 1988, Han and Hall 2006). High stumps reduce recovered volume and increase costs because of damage to the machines and trees breaking after being felled across high stumps. When comparing mechanised with motor-manual felling, Warkotsch (1988), Kewley and Kellogg (2001) and Han and Hall (2006) found that the latter resulted in more fibre loss because of higher stump heights and poor felling technique. In addition, Han and Hall (2006) found that using a chain saw head, instead of a disk saw on the feller-buncher, and ensuring that chain saws are well-maintained and sharp to give cleaner cuts, will further reduce fibre loss because of saw kerf. Educating machine operators on the importance of lowering stumps is a simple way of decreasing fibre loss resulting from high stumps (Warkotsch 1988, Han and Hall 2006). Furthermore, Shaffer (1992) found that the use of shears, instead of saw heads, maximised merchantable timber utilisation through lower stumps but results in losses in log quality because of lower stem shatter.

In summary and based on the literature, the best harvesting systems for minimisation of fibre loss are, in order of priority, the motor-manual felling TL system, the mechanical FT system with roadside processing and the CTL harvester/forwarder system. A problem, however, with the reports referred to is that they typically are concerned with the analysis of only one harvesting operation and only one system.

Assessment and measurement of biomass losses

There are no applicable biomass/fibre loss assessment methodologies that can be referenced from the literature. Gingras (1992) developed two indices of fibre recovery efficiency to compare the fibre recovery efficiency of six harvesting systems. The first (Equation 1), is used to estimate the proportion of merchantable fibre recovered in comparison to the amount of fibre left in the cut compartment.

$$\text{Fibre recovery index (\%)} = \frac{100V_1}{(V_1+V_S)} \tag{1}$$

where V_1 = volume recovery (m³ ha⁻¹) and V_s = merchantable slash (m³ ha⁻¹).

The second index (Equation 2) is the fibre yield index, which is used to estimate the fibre recovered (or lost) compared to what is expected from a preharvest assessment. In South Africa typically less is harvested than predicted (Ham et al. 2010).

$$\text{Fibre yield index (\%)} = \frac{100V_{m1}}{V_{m2}} \qquad (2)$$

where V_{m1} = merchantable volume recovered ($m^3\,ha^{-1}$) and V_{m2} = merchantable volume from cruise ($m^3\,ha^{-1}$).

What is clear from the literature review is that most of the published work concerning the tracking of fibre losses has occurred in New Zealand, Canada and some other Northern Hemisphere countries, and that in South Africa information is lacking.

Objective of the study

The objective of the study was to quantify the type and magnitude of fibre and value losses in typical softwood saw timber semimechanised tree-length harvesting operations from felling through merchandising in South Africa. Merchandising occurred both at the roadside and at centralised merchandising yards. The study related specific losses to the cause of the losses. One of the subobjectives of this work was to study the harvesting systems broadly to eliminate the shortfall identified in the literature from just studying individual operations in isolation of one another.

The study was limited to the following:

(1) semi-mechanised softwood saw timber harvesting operations
(2) felling methods are either motor-manual (chain saw) felling or by drive-to-tree feller-bunchers equipped with continuous disk saws
(3) extraction was by grapple or cable skidder
(4) all crosscutting was done motor-manually with chain saws
(5) the study ended once the final assortments had been merchandised, albeit at either the roadside or merchandising yard
(6) no distinction was made between species of pines studied because of limited number of sites, harvesting system and skidder matching
(7) no log value optimisation was included in this study.

Materials and methods

Study sites

The study was confined to softwood saw timber operations in South Africa, including the winter (Western Cape), year-round (Southern Cape) and summer (Mpumalanga and KwaZulu-Natal) rainfall areas (Table 1).

The study represented all the major pine saw timber growers in the country and was conducted over a period of 18 months, which allowed the selection of relatively similar sites in terms of terrain classification and weather conditions (non-rainy periods) and to accommodate the different requirements of the treatments that make up the study. The study entailed tracking fibre and value losses in individual trees (*N*) of a selected sample, over a number of sites, operating conditions, harvesting systems and tree dimensions, through felling to merchandising of the tree-lengths into log assortments.

Treatments

The eight individual treatments (Figure 1a–d) comprised a combination of merchandising locations, average compartment tree size classes and felling methods (Table 2). The main segregation of the treatments was based on merchandising location (roadside and centralised yard). The felled tree-lengths were extracted to roadside, log scaled and merchandised, or transported as tree-lengths to a centralised merchandising yard for log scaling and merchandising. The treatments were then further divided based on average tree size for the compartment (compartment volume <1 m³ stem⁻¹ and >1 m³ stem⁻¹) and felling method (motor-manual and mechanised). This breakdown resulted in eight different harvesting treatments. In all cases an attempt was made to achieve a minimum sample size of 20 trees per treatment.

The original intention of the study was to include a degree of terrain difficulty (slope). This was later abandoned because of the difficulty of doubling the number of replications, and finding sites and operations to accommodate this degree of complexity. The three treatment variables (merchandising location, average compartment tree volume class and felling method) were selected since they significantly influence decisions related to changing the form of the original tree. Tree size has a potential bearing on the felling method and the potential loss of fibre from breakage during felling.

Merchandising location

Merchandising (i.e. log scaling and subsequent crosscutting of tree-lengths into assortments) took place at either a continuous roadside landing or at a centralised merchandising yard. All crosscutting was done motor-manually with chain saws.

Average compartment tree size class

Compartments were divided into two volume classes (referred to as compt. vol.); compartments with average merchantable tree volume (under bark) of <1.0 m³ stem⁻¹ and those with merchantable volume (under bark) >1.0 m³ stem⁻¹. In both cases a minimum 10 cm top-end diameter under bark was maintained.

Felling and extraction

The two felling methods selected for the study were motor-manual felling by chain saw and mechanised felling using drive-to-tree feller-bunchers with continuous disk saw. In both cases, chain saw operators were responsible for the motor-manual debranching and topping of the felled stems. Once felling and stem preparation were completed, extraction of the tree-lengths commenced to roadside landings by grapple (mechanised felling) or cable skidders (motor-manual felling). For both felling methods, stems were skidded individually to the roadside once the relevant data had been collected. The sequences of operations in each harvesting system are as illustrated in Figure 1a–d (each system in turn was applied to the compartment volume classes).

Table 1: Treatments and treatment definitions, terrain classification (Erasmus 1994), geographic location of individual treatments, and sample sizes

Site and terrain classification	Roadside merchandising				Centralised merchandising yard			
	Compartment < 1 m³		Compartment > 1 m³		Compartment < 1 m³		Compartment > 1 m³	
	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling
	1 RS<1MM	2 RS<1Mech	3 RS>1MM	4 RS>1Mech	5 MY<1MM	6 MY<1Mech	7 MY>1MM	8 MY>1Mech
Mpumalanga	$N = 20$	$N = 30$	$N = 40$	$N = 30$				
Ground conditions*	Good	Good	Good	Very good				
Ground roughness	Slightly uneven	Slightly uneven	Slightly uneven	Slightly uneven				
Slope (degrees)	≤6.5 Undulating	≤6.5 Regular	≤6.5–19% Undulating	≤6.5 Regular				
KwaZulu-Natal					$N = 30$		$N = 20$	
Ground conditions					Very good		Very good	
Ground roughness					Slightly uneven		Slightly uneven	
Slope (degrees)					≤6.5 Regular		≤2 Undulating	
Southern Cape						$N = 32$		$N = 30$
Ground conditions						Very good		Very good
Ground roughness						Smooth		Smooth
Slope (degrees)						≤6.5 Regular		≤6.5 Regular
Western Cape	$N = 20$		$N = 20$					
Ground conditions	Good		Good					
Ground roughness	Slightly uneven		Slightly uneven					
Slope (degrees)	≤6.5 Undulating		≤6.5–11 Undulating					
Total *N*	40	30	60	30	30	32	20	30

* Estimated at time of field survey in dry state

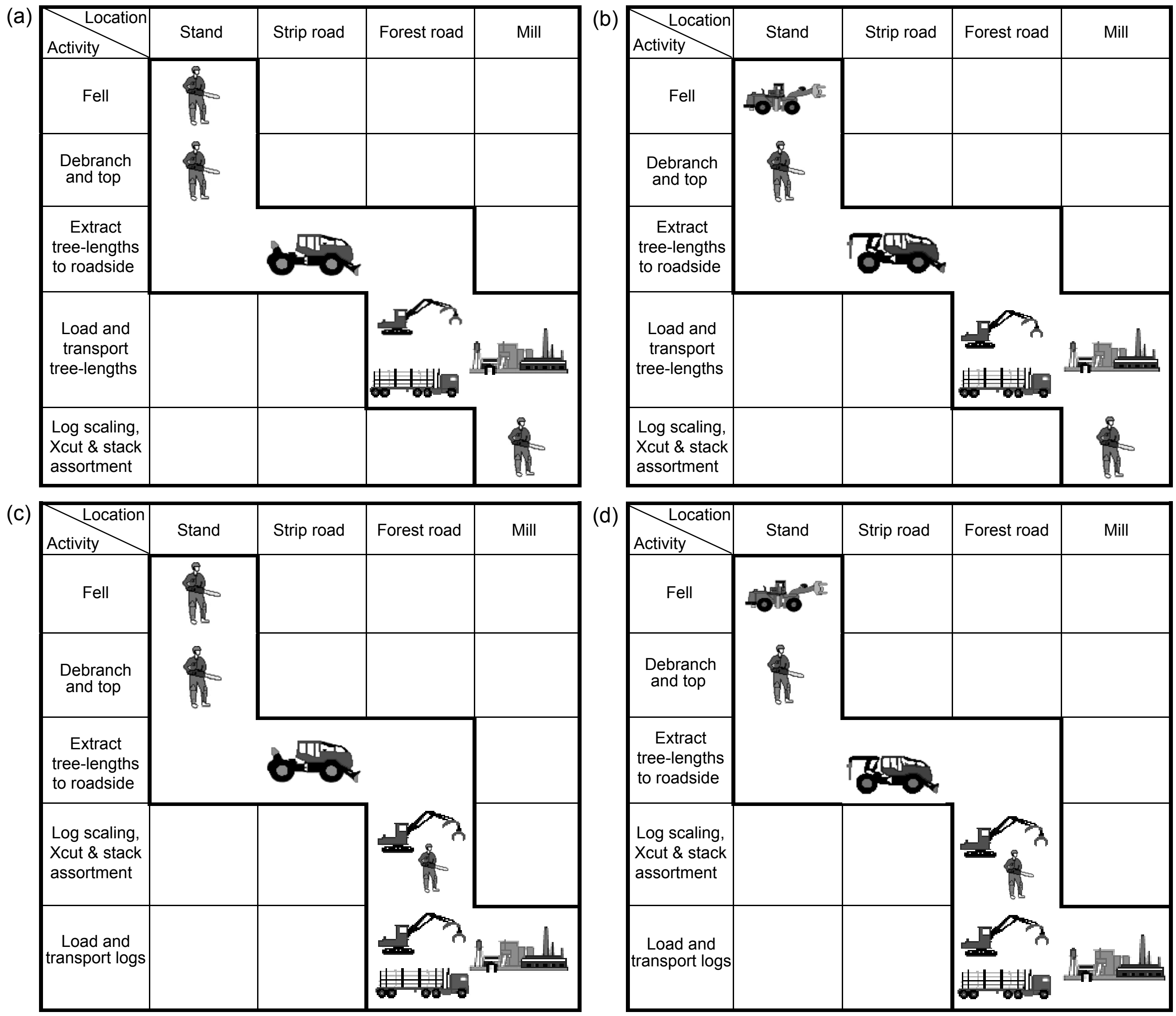

Figure 1: (a) Motor-manual felling and merchandising at centralised merchandising yard, (b) mechanised felling and merchandising at centralised merchandising yard, (c) motor-manual felling and merchandising at roadside landing, and (d) mechanised felling and merchandising at roadside landing

Terrain classification

Terrain is classified according to Erasmus (2004) and is presented in Table 1. As only ground-based harvesting was studied, site slopes ranged between level ground and 11 degrees (Table 1) in any of the individual treatments. There was little variation between treatments for both ground roughness and ground conditions and in all cases could be classified as good (i.e. offering no operational limitations). All field work was conducted only during dry weather conditions in order to simplify measurements and subsequent data recoding.

Sample sizes

In all cases a minimum sample size of 20 trees per treatment was determined to be necessary (Kanawaty 1992) for estimating fibre loss within 5% of the true mean in 95% of the time (Table 1).

Data collection

The study methodology involved tracking a sample of trees from felling, through all supply chain phases up to and including the merchandising of log assortments at either roadside or centralised merchandising yard. In this way fibre and quality losses at each point in the supply chain were determined. Activities occurred in the following sequence:

- A sample of felled trees in the compartment was chosen for analysis provided each individual tree's stump could be identified.
- Each stump and corresponding tree butt-end was numbered chronologically with fluorescent paint for easy identification. Numbering was necessary to be able to associate each stump with a particular tree and to check that the entire stem or section of the stem reached the roadside during extraction.

Table 2: Categories and definitions of fibre utilisation or losses

Category	Description
Stump volume loss	Volume difference between actual felling height and a reasonable felling height above mineral soil (refer to Materials and methods for definition of reasonable felling height)
Felling saw kerf volume loss	The width of the saw kerf as volume loss. Dimensions taken into account to determine volume were 0.8 cm and 5.5 cm for bar and chain and continuous saw disk, respectively
Crosscut saw kerf volume loss	The width of the crosscut saw (chain saw) kerf as volume loss. Dimension used is 0.8 cm as all crosscutting was done by chain saw
Log trimming volume loss	Volume related to the mandatory log allowance of at least 10.0 cm allocated to each sawlog assortment
Incorrect log trimming allowance volume loss	Log scaling activities that result in more or less than the actual 10 cm log allowance being allocated to sawlogs. Both cases result in volume loss because of unnecessary wood removal in the saw mill. In particular, if less than the 10 cm log allowance is allocated, the specific log is downgraded to the next (shorter) length class resulting in volume loss
Top volume loss	Any pieces in excess of 10.0 cm (diameter under bark) not merchandised
Excessive trimming and removal of merchantable wood volume loss	Merchantable volume removed because of defect trimming. This volume loss includes both the defect section (pulled fibres, barber chairs, lower stem splits, and stem breakages from ground or obstacle impact) and any excessive trimming on either side of the defect. Any other defects such as decayed wood and out of log specification sections (e.g. knot clusters and excessive sweep) are regarded as non-merchantable wood and excluded as merchantable wood volume loss
Total volume loss	The sum of: stump volume loss, saw kerf volume loss (fell and crosscut), log allowance volume loss, incorrect log allowance allocation volume loss, top volume loss, and excessive removal of merchantable wood volume loss

- Simultaneously, the tip of the particular tree, whether it was cross-cut at 10.0 cm or whether it had broken off at some point, was clearly marked with the corresponding stump and tree number.
- If a piece did break off, and was not collected and skidded to the landing, the enumerators traced this piece in the stump area and recorded its dimensions as timber being left in-field and hence lost fibre.

The following were recorded as fibre losses: high stumps (defined below), removal of damaged fibre during log scaling; removal of too much fibre when making a decision to remove damaged or defect fibre; incorrect and inappropriate log scaling practices; amount of log trimming allowance; both felling and crosscutting saw kerf widths; and utilisable wood being left in-field (Table 2). For the purposes of the study, it was accepted that any wood piece with a diameter smaller than 10.0 cm (under bark) would not be taken into account. All broken tops of diameter greater than 10.0 cm (under bark) formed part of the study. The basis for the percentage volume loss calculations mentioned above was the potential net merchantable volume of each stem studied. With respect to determining volume loss, the enumerator, an experienced forest engineer, evaluated each case and determined whether losses were being experienced as a result of specific actions of the harvesting team.

Stump height was measured as the distance between the points where the butt starts to flare or the top of an adjacent obstacle, to the average top of the stump. The formula for the volume of the frustum of a neiloid (Equation 3) was used to calculate stump volume (Ride 1999):

$$\text{Volume} = \frac{H}{4}\,\frac{\left(a+\left(a^2b\right)^{1/3}+\left(ab^2\right)^{1/3}+b\right)}{1\,000\,000} \qquad (3)$$

where $a = \pi(d_1/2)^2$, $b = \pi(d_2/2)^2$, d_1 and d_2 are the bottom and top diameters (cm) of the stump, and H equals height (cm) of the stump

Kerf widths were recorded for both crosscutting and felling, and in turn converted to volume. For chain saw felling and crosscutting, a kerf width of 0.8 cm was used, whereas for the feller-buncher with continuous disk saw 5.5 cm was used. Once felling, debranching and topping were completed, all stumps evaluated, and the stumps and tree-lengths (butts and tips) marked, then the tree-lengths were extracted to roadside. At the roadside log scaling commenced or the tree-lengths were loaded and transported to a centralised merchandising yard. No preemptive cutting was needed as in all cases trucks remained on company roads. In each case log scaling occurred under completely different circumstances; roadside scaling was at the roadside, whereas merchandising yard scaling occurred under improved underfoot and work conditions and with tree-lengths elevated on skids to facilitate crosscutting activities. Skids supposedly facilitate both log scaling and crosscutting activities (Warkotsch 1988). When scaling in-field, the log scalers cover longer distances to follow the sequence of tree-lengths being skidded to roadside and in most cases work with tree-lengths lying flat on the ground. During the study no inclement weather conditions were experienced and, although it was assumed that the operators and log scalers were adequately trained, as communicated by harvesting managers, for their specific tasks and also conversant with current log specifications, differences in training levels are expected between and within regions. Log scaling proceeded with log scalers marking out log assortments on the stems using either lumber crayon or by physically marking the log with a scar (using a handsaw or hatchet). The scalers used scaling rods with standardised log dimensions marked on the rod. Before actual crosscutting took place, thin-end (over-bark) diameter and length of each log marked out was recorded. This in turn allowed measurement of the actual log trimming allowance being allocated to sawlogs. Non-merchantable timber, merchantable volume losses and top volume losses (Table 2) were collected during this phase of data recording. The tree-lengths were then crosscut and the logs loaded onto a logging truck for transport to the mill. As for the centralised merchandising yards the same procedure as above was followed once the tree-lengths had reached the merchandising yard.

To determine sawlog fibre value recovered during the study, all sawlogs along with their actual dimensions were analysed with the software package SIMSAW 6 (Wessels et al. 2006). SIMSAW 6 simulates the conversion of round logs to lumber given inputs of log dimensions and log form. Sawing variables such as sawing pattern and kerf, as well as shrinkage and final product dimensions (Wessels et al. 2006) are included. The SIMSAW 6 output provides information on total log volume sawn, dry and wet volume recovered percentage, board value recovery (R m^{-3}) and net value board recovery (R m^{-3}). Values are derived from current standard price lists for all grades of boards and round logs produced.

To calculate the resultant area of plantation that would need to be harvested to supply the additional fibre lost because of the fibre losses, it is understood that this volume of roundwood is a net volume (i.e. less fibre losses). To calculate the gross fibre (i.e. fibre delivered plus the fibre losses) required to be actually harvested, the percentage fibre loss must be added to the volume delivery, i.e. more fibre needs to be harvested than is delivered to the sawmill.

Data analysis

In the case of veneer and sawlogs in South Africa a trimming allowance of up to 10 cm is added to each log to ensure that logs are of nominal length (von dem Bussche 1987). This log trimming allowance is termed 'log trimming allowance volume loss' (Table 2). If more (or less) than the 10 cm trimming allowance was allocated to a certain log it was termed an 'incorrect log trimming allowance volume loss' (Table 2). No log trimming allowance is added to the nominal length of pulp/chip logs. These types of circumstances occurred with logs having a diameter less than 15 cm under bark and/or logs with a length less than 2.4 m.

Using the thin-end diameter and length of each log or waste piece, the under-bark volume was calculated using Equation 4 (Bredenkamp 2000):

$$V = \frac{\left(d_t + \frac{l}{2}\right)^2 \pi}{40\,000\ l} \qquad (4)$$

where d_t = under-bark diameter at the thin end of a log (cm), l = length of the log (m), and V = under-bark volume (m^3).

Not only was the actual volume of the log calculated using this formula, but also the volume of what the mill had purchased, the volume of the log allowance and the volume of any additional volume losses. Equation 4 was also used to calculate the volume of saw kerfs by using the saw kerf width as the length and the under-bark diameter of the log at that point, as well as volume from decay or logs affected by forks and broken ends. The crosscut saw kerf volume loss is subtracted from the category 'log trimming allowance allocation volume loss', if present on a log. If there is no log trimming allowance on the log, or it is less than 10 cm the crosscut saw kerf is subtracted from the actual nominal log length. Equation 4 was also used to determine the volume of the merchantable losses and top volume losses (Table 2). The summary information was then used for comparing each compartment in terms of timber yield and value.

Statistical analysis

Both two-way and three-way factorial analysis of variance (ANOVA) designs with at least 20 replications (Table 1) per treatment were used to interpret the data. For excessive stump height, stump volume loss, felling saw kerf volume loss and top volume loss, a two-way ANOVA factorial design was used. For the balance of the volume loss categories, three-way ANOVA factorial designs were used, except in the case of incorrect log allowance allocation volume loss and total volume loss, which showed no three way interaction, therefore a two-way ANOVA was applied. Each treatment had two merchandising locations (roadside and centralised yard), two compartment average tree size classes (compt. vol. < 1 m^3 and > 1 m^3) and two felling methods (motor-manual and feller-buncher).

The statistical analysis for significance was done with a Factorial ANOVA using STATISTICA 10 software (StatSoft, Tulsa). The first null hypothesis tested was that of no treatment interaction effects. If this hypothesis was not rejected then the levels behaved consistently between the factors analysed; thus, individual factors were compared. However, if the hypothesis was rejected, it was sufficient to examine the interaction effects (Milton and Arnold 1999). If significant differences (α = 0.05) between treatment means or a significant interaction effect were found, the significant differences between individual means were determined using a *post hoc* Bonferroni test or a Newman-Keuls test. The Newman-Keuls test was used only when the Bonferroni test was unable to determine where the differences between means occurred; and this applied only to crosscut saw kerf and top volume loss.

One complication of the data is the unbalanced design of the experiment. Although all treatment types were measured, it was not possible to obtain data for each treatment in each geographical area (Table 1). Levene's test found that the variance of each geographical area for the different volume loss categories was not homogenous ($p < 0.05$). As such, there were significant differences in volume losses dependent on area, which may have been a confounding factor in this experiment. The residuals for all data sets were normally distributed and hence neither non-parametric statistical methods nor transformations were required.

Results

ANOVA results by fibre loss categories

The section below represents the interpretation of ANOVAs for the individual categories of volume loss percentage.

Each interpretation is accompanied by a graphical representation showing the least squared means dependent on the particular main effects. Similar means are marked with the same letter. Bars indicate 95% confidence interval in each of the accompanying figures (Figure 2a–g).

Excessive stump heights (cm)
There was no significant interaction between compt. vol. and felling method ($p = 0.3536$, $p = 0.5622$). The main effects, compt. vol. and felling method, also showed no significant differences ($p = 0.1165$) ($\alpha = 0.05$) between treatments. Measured stump heights were 7 cm above acceptable stump height.

Stump volume loss percentage
A two-way ANOVA was run for stump volume loss (%) with compt. vol. and felling method. The interaction of compt. vol. and felling method had a significant effect ($p < 0.001$) on stump volume loss percentage (Figure 2a). The *post hoc* Bonferroni test showed no significant differences for compt. vol. > 1 m^3 trees felled mechanically or motor-manually (0.67%). A significant difference was found between mechanical and motor-manual felling in compartments with compt. vol. < 1 m^3 (0.074% vs 1.26%). A significant difference was also found for compt. vol. < 1 m^3 and > 1 m^3 for mechanically felled trees (0.07% vs 0.79%). There was also a significant difference for compt. vol. < 1 m^3 and > 1 m^3 motor-manually felled trees (1.26% vs 0.58%).

Felling saw kerf volume loss percentage
A two-way ANOVA was run for felling saw kerf volume loss (%) with compt. vol. and felling method. The interaction of compt. vol. and felling method was significant ($p < 0.05$) on felling saw kerf volume loss (%) (Figure 2b). The Bonferroni test revealed no significant difference between compt. vol. < 1 m^3 and > 1 m^3 that were motor-manually felled (0.15%). A significant difference was found between mechanically felled compt. vol. < 1 m^3 and > 1 m^3 (1.0% vs 0.88%), and the motor-manually felled compartments (0.15%). The lower percentage of fibre loss for compt. vol. > 1 m^3 during mechanised felling is most likely because of the larger average compt. vol. (1.45 m^3) of treatment 8 (MY>1MECH).

Crosscut saw kerf volume loss percentage
A three-way ANOVA with cross-cut saw kerf volume loss (%) as the dependent variable showed significant interaction between compt. vol., felling method and merchandising location ($p < 0.05$). Given the increased number of variables from the three-way interaction, two two-way ANOVAs for each merchandising location were run in order to simplify the *post hoc* Bonferroni interpretation.

Roadside
A two-way ANOVA using crosscut saw kerf volume loss (%) as the dependent variable with compt. vol. and felling method showed a significant interaction between compt. vol. and felling method ($p < 0.05$) (Figure 2c). The *post hoc* Bonferroni test was not conclusive. A *post hoc* Newman-Keuls test showed there was no significant difference between compt. vol. > 1 m^3 mechanical and motor manual felling (0.21%). There was a significance difference for compt. vol. < 1 m^3 between mechanical and motor-manual felling (0.20% vs 0.24%) ,although neither was significantly different from compt. vol. > 1 m^3 (0.21%).

Merchandising yard
A two-way ANOVA using crosscut saw kerf volume loss (%) as the dependent variable with compt. vol. and felling method showed no significant interaction ($p = 0.156$). Interpreting the main effects showed that felling method was significant ($p < 0.05$) with volume losses from mechanical felling less than from motor-manual felling (0.17% vs 0.20%). The effect of compt. vol. was not significant.

Log allowance volume loss percentage
A three-way ANOVA with log allowance volume loss (%) as the dependent variable and using compt. vol., felling method and merchandising location showed a significant interaction between compt. vol., felling method and merchandising location ($p < 0.05$).. Given the increased number of variables from the three-way interaction, two two-way ANOVAs for both merchandising locations were run.

Roadside
A two-way ANOVA of log allowance volume loss (%) revealed no significant interaction between compt. vol. and felling method. Interpreting the main effects showed that felling method was significant ($p < 0.05$) with volume losses from motor-manual felling less than from mechanical felling (1.47% vs 1.84%). The effect of compt. vol. was not significant.

Merchandising yard
A two-way ANOVA of log allowance volume loss (%) showed a significant interaction of compt. vol. and felling method ($p < 0.05$) (Figure 2d). A *post hoc* Bonferroni test showed a significant difference between compt. vol. > 1 m^3 mechanically felled trees and the other three treatments (1.26% vs 1.66%). There was no significant difference between compt. < 1 m^3 mechanically felled trees, between compt. vol. > 1 m^3 motor-manually felled trees or between compt. vol. < 1 m^3 motor-manually felled (1.66%).

Incorrect log allowance volume loss percentage
A three-way ANOVA between compt. vol., felling method and merchandising location showed no significant interaction between the three variables ($p = 0.842$). Interpreting the main effects showed that compt. vol. was not significant in any combination with the other two effects or individually. Therefore, a two-way ANOVA of felling method and merchandising location was done and a significant interaction found ($p < 0.05$) (Figure 2g). The *post hoc* Bonferroni test showed a significant difference between roadside merchandising and merchandising-yard merchandising for mechanical felling (1.29% vs 0.24%). A significant difference was found for merchandising yards between mechanical and motor-manual felling (0.24% vs 0.52%). A significant difference was also found for roadside merchandising between mechanical and motor-manual felling (1.29% vs 0.45%). There was also a significant difference between motor-manual felling

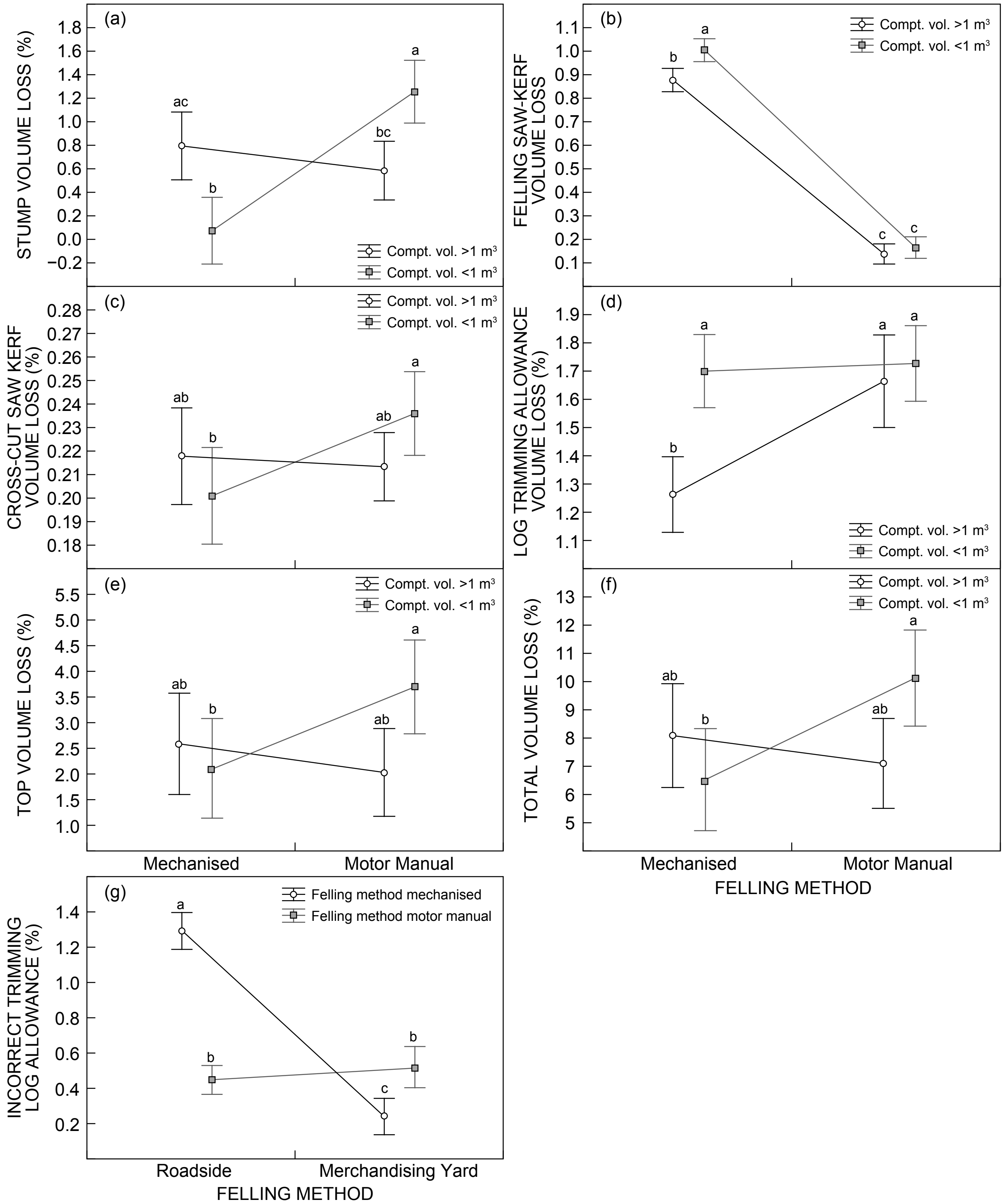

Figure 2: ANOVA interpretations for the individual categories of volume loss percentage. (a) Stump volume loss (%) least squared means dependent on compt. vol. and felling method. (b) Felling saw kerf volume loss (%) least squared means dependent on compt. vol. and felling method. (c) Crosscut saw kerf losses (%) at the roadside merchandising location based on compt. vol. and felling method (*post hoc* Newman-Keuls indicates that mechanically felling in compt. vol. <1 m³ [a] is significantly different from motor-manual felling in compt. vol. <1 m³ [b]). (d) Log trimming allowance volume losses (%) at the merchandising-yard merchandising location based on compt. vol. and felling method. (e) Top volume loss based on compt. vol. and felling method. Although difficult to see, the *post hoc* Newman-Keuls indicate that motor-manual felling in compt. vol. <1 m³ (a) is significantly different from mechanised felling in compt. vol. <1 m³ (b). (f) Top volume loss based on compt. vol. and felling method. Although difficult to see, the *post hoc* Newman-Keuls indicates that motor-manual felling in compt. vol. <1 m³ (a) is significantly different from mechanised felling in compt. vol. <1 m³ (b). (g) Incorrect trimming log allowance allocation volume loss (%) dependent on merchandising location and felling method (compt. vol. was not significant and therefore not included)

at roadside and mechanised felling at merchandising yards (0.45% vs 0.24%). There was no significant difference between roadside merchandising and merchandising-yard merchandising for motor-manual felling (0.47%).

Top volume loss percentage

A two-way ANOVA with top volume loss (%) as the dependent variable and compt. vol. and felling method showed that there was a significant interaction ($p < 0.05$). The *post hoc* Bonferroni test found that all means were not statistically different; however, this did not correspond to the significance shown during the ANOVA, thus a *post hoc* Newman-Keuls test was used. A *post hoc* Newman-Keuls's test found that there was a significant difference between compt. vol. < 1 m^3 mechanically felled and motor-manually felled trees (2.09% vs 3.70%). There was no significant difference for compt. vol. > 1 m^3 between mechanical felling and motor-manual felling (2.27%). Compt. vol. > 1 m^3 did not differ significantly from compt. vol. < 1 m^3 regardless of felling method (Figure 2e).

Excessive trimming and removal of merchantable wood volume loss percentage

A three-way ANOVA with excessive trimming and removal of merchantable wood volume loss (%) as the dependent variable and using compt. vol., felling method and merchandising location, showed a significant interaction between compt. vol., felling method and merchandising location ($p < 0.05$). Given the increased number of variables from the three-way interaction, two two-way ANOVAs for each merchandising location were run in order to simplify the interpretation of the *post hoc* Bonferroni test.

Roadside

The two-way ANOVA between compt. vol. and felling method for roadside merchandising showed that the interaction between compt. vol. and felling method was not significant ($p = 0.168$). The effect of felling method was significant ($p < 0.05$) and mechanical felling had less volume loss than motor-manual felling (0.48% vs 1.67%). The effect of compt. vol. was not significant ($p = 0.337$).

Merchandising yard

The two-way ANOVA between compt. vol. and felling method for merchandising-yard merchandising did not find the interaction between compt. vol. and felling method to be significant ($p = 0.157$). Neither main effect, compt. vol. nor felling method, was found to be significant ($p = 0.150$ and $p = 0.675$). A *post hoc* Bonferroni's test corroborated this result and found all means to be similar (2.47%).

Total volume loss percentage

A three-way ANOVA using total volume loss (%) as the dependent variable and merchandising location, compt. vol. and felling method found that the three-way interaction was not significant ($p = 0.090$). However, the compt. vol. and felling method interaction on total volume loss (%) was significant ($p < 0.05$). Merchandising location did have a significant individual effect ($p < 0.05$). This means that the two-way interaction between compt. vol. and felling method occurred consistently between the two merchandising locations (roadside and merchandising yard). Hence, a two-way ANOVA on all responses (both merchandising locations) between compt. vol. and felling method yielded a significant difference (Figure 2f). The *post hoc* Bonferroni test showed that there was a difference between mechanised and motor-manual felling for compt. vol. < 1 m^3 (6.49% vs 10.09%). There was no significant difference between felling methods for compt. vol. > 1 m^3 (7.49%).

Data and ANOVA summary

To facilitate interpretation of the ANOVA results, Tables 3–4 and Figure 3a–f summarise study tree and tree volume statistics, and all significant and non-significant volume loss percentages by treatments and categories.

Number of logs over- and under-scaled during log scaling

Table 5 shows the number of logs scaled over or under the specified log dimension (including the log allowance with sawlogs) as a percentage of the total number of logs made.

Fibre value recovery

Table 6 shows the output from the SIMSAW 6 software on sawtimber logs made at merchandising yards and at roadside landings, in terms of log volume, number of logs, the value of product recovered from these logs by the sawmill, both net and gross value recovered in terms of boards, and the log value as per current log prices.

Table 7 lists opportunities forgone because of the fibre volume losses during harvesting operations as outlined in the study.

To calculate net product value of sawlogs recovered, the gross value recovered is divided by log volume for each specific merchandising location. To calculate the value of plantation roundwood sawlogs sales forgone or lost average log cost is used from Table 6. Average sawlog cost is in turn calculated from standard industry log prices, which are based on individual log dimensions (length and diameter), and general veneer and sawlog specifications.

Discussion

Supply chain management studies as a rule evaluate projects on three aspects: fibre yields, fibre quality and cost. The present study concentrated on fibre yields from softwood sawtimber operations and the cost/revenue of this fibre lost.

Fibre yield

Total volume loss

On average, across all treatments, 92.07% of total utilisable tree volume is being recovered as useful fibre. Considering an average annual delivery of 4.9 million m^3 of softwood sawtimber (FSA 2009), the 7.932% volume of wood not recovered equates to 421 700 m^3 more volume being felled than is necessary to provide for the same annual roundwood delivery. By using this study's weighted average compt. vol. of 0.934 m^3, and an average stand volume of 330 m^3 ha^{-1}, an additional 1 277 ha of plantation is felled to produce the same annual volume. Total volume losses range from 6.49% (Figure 2f) in the case of compt. vol.

Table 3: Study tree and tree volume summary statistics

	Roadside merchandising				Centralised merchandising yard			
	Compartment <1 m³		Compartment >1 m³		Compartment <1 m³		Compartment >1 m³	
	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling
	1	2	3	4	5	6	7	8
	RS<1MM	RS<1MECH	RS>1MM	RS>1MECH	MY<1MM	MY<1MECH	MY>1MM	MY>1MECH
Net utilisable volume of N (m^3)	20.01	23.16	66.02	30.23	22.39	22.04	20.20	42.14
Average utilisable tree volume (m^3 $stem^{-1}$)	0.499	0.766	1.010	1.041	0.770	0.766	1.096	1.453
Average stems.ha^{-1}	452	398	315	320	386	415	350	315
Average volume (m^3 ha^{-1})	226	306	347	333	298	315	354	457
Number of trees tracked	40	30	60	30	30	32	20	30
Utilisable volume (V; m^3 ha^{-1})	226	306	347	333	298	315	354	457

Table 4: Summary of ANOVA results per treatment and volume loss category and volume losses per treatment. Total volume loss is the sum of individual treatment volume losses ± SE. Table includes total volume loss and volume recovery. Values in rows with the same superscript are not significantly different at the 95% level

	Roadside merchandising				Centralised merchandising yard			
	Compartment < 1 m³		Compartment > 1 m³		Compartment < 1 m³		Compartment > 1 m³	
	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling	Motor-manual felling	Mechanised felling
	1	2	3	4	5	6	7	8
	RS<1MM	RS<1MECH	RS>1MM	RS>1MECH	MY<1MM	MY<1MECH	MY>1MM	MY>1MECH
Crosscut saw kerf volume losses (%)	0.24 ± 0.01^{a}	0.20 ± 0.01^{b}	0.21 ± 0.00^{ab}		0.17 ± 0.00^{c}			
Log trimming allowance volume loss (%)	1.47 ± 0.05^{a}	1.84 ± 0.06^{b}	1.47 ± 0.05^{a}	1.84 ± 0.06^{b}		1.66 ± 0.00^{c}		1.26 ± 0.08^{d}
Excessive removal of merchantable wood volume loss (%)	1.56 ± 0.28^{a}	0.48 ± 0.36^{b}	1.56 ± 0.28^{a}	0.48 ± 0.36^{b}	2.47 ± 0.52^{c}			
Stump volume loss (%)	1.26 ± 0.14^{a}	0.07 ± 0.14^{b}	0.58 ± 0.13^{bc}	0.79 ± 0.15^{ac}	1.26 ± 0.14^{a}	0.07 ± 0.14^{b}	0.58 ± 0.13^{bc}	0.79 ± 0.15^{ac}
Felling saw kerf volume loss (%)	0.15 ± 0.00^{c}	1.0 ± 0.02^{a}	0.15 ± 0.00^{c}	0.88 ± 0.03^{b}	0.15 ± 0.00^{c}	1.0 ± 0.02^{a}	0.15 ± 0.00^{c}	0.88 ± 0.03^{b}
Top volume loss (%)	3.70 ± 0.46^{a}	2.09 ± 0.49^{b}	2.27 ± 0.11^{ab}		3.70 ± 0.46^{a}	2.09 ± 0.49^{b}	2.27 ± 0.11^{ab}	
Incorrect log trimming allowance volume loss (%)	0.45 ± 0.00^{a}	1.29 ± 0.05^{b}	0.45 ± 0.00^{a}	1.29 ± 0.05^{b}	0.45 ± 0.00^{a}	0.24 ± 0.05^{c}	0.45 ± 0.00^{a}	0.24 ± 0.05^{c}
Total volume loss (%)	8.83	6.97	6.69	7.76	9.86	7.70	7.75	8.08
Utilisable volume (m^3 ha^{-1}) (V)	226.00	306.00	347.00	333.00	298.00	315.00	354.00	457.00
Total volume loss (m^3 ha^{-1}) (V * %)	19.96	21.33	23.94	25.84	29.38	24.26	27.44	36.93
Actual volume recovered (m^3 ha^{-1})	206.04	284.67	323.06	307.16	268.62	290.74	326.56	420.07

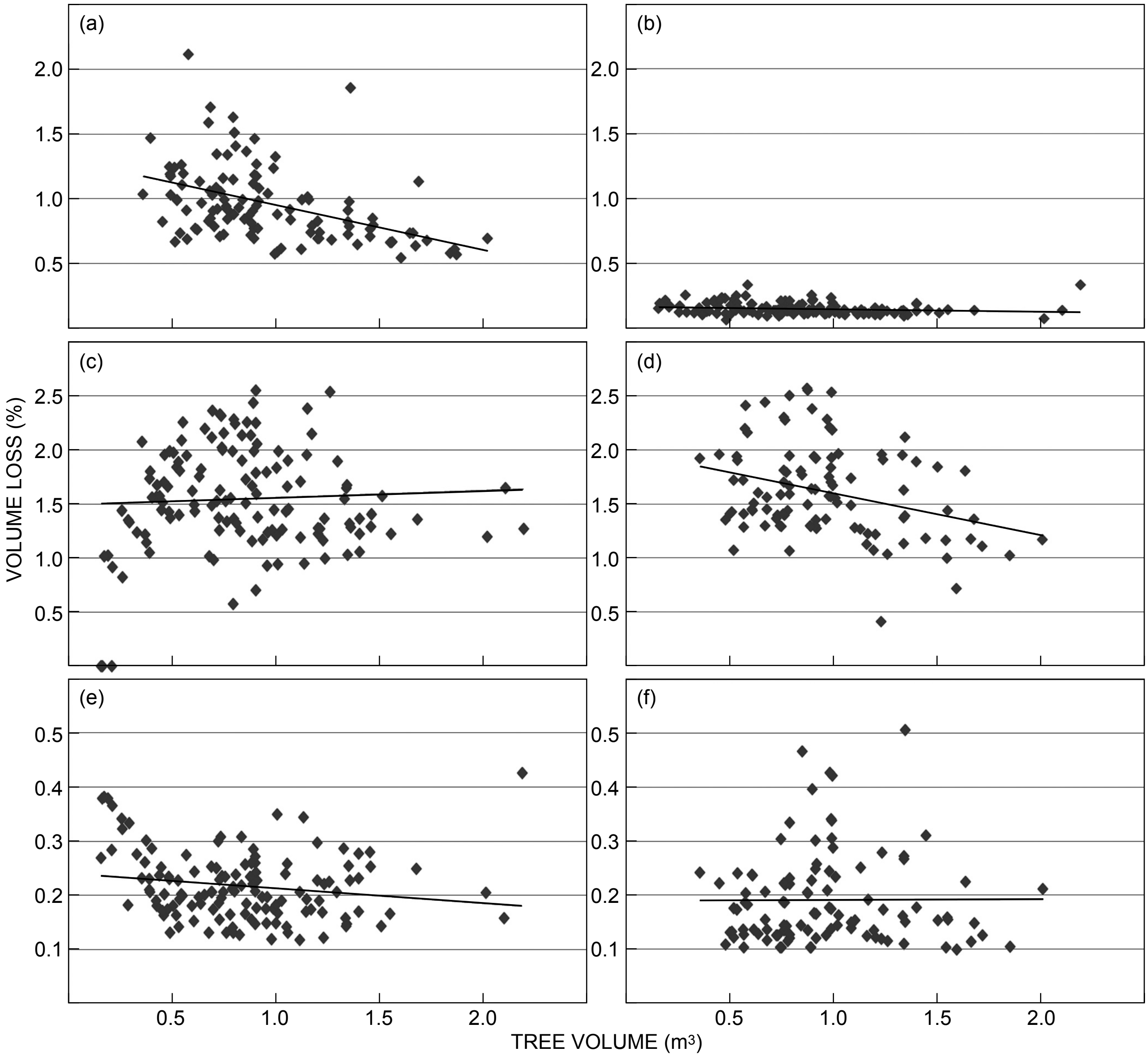

Figure 3: (a) Felling saw kerf volume loss percentage of mechanised felling (r^2 = 0.2262***, p < 0.001, n = 122), (b) felling saw kerf volume loss percentage of motor-manual felling (r^2 = 0.0281*, p < 0.05, n = 150), (c) log allowance volume loss percentage of roadside merchandising (r^2 = 0.0991^{ns}, p =0.228, n = 112), (d) log allowance volume loss percentage at merchandising yard (r^2 = 0.1373***, p < 0.001, n = 150), (e) crosscut saw kerf volume loss percentage of roadside merchandising (r^2 = −0.1444^{ns}, p = 0.068, n = 112), (f) crosscut saw kerf volume loss percentage of merchandising-yard merchandising (r^2 = −0.0965^{ns}, p = 0.311, n = 150)

< 1 m^3 mechanically felled trees and 10.09% for compt. vol. < 1 m^3 motor-manually felled trees. The study also found that merchandising location, either roadside landing or a remote merchandising yard, played no significant role in either facilitating the gain of, or causing the loss of, potentially utilisable fibre. However, compt. vol. < 1 m^3 motor-manually felled trees produce greater total volume loss than the other treatments (10.09% vs 6.49% and 7.49%). Table 4 shows the potential loss in merchantable volume per hectare under the treatments described in the study. Smaller compt. vol. trees produced greater percentage volume loss in the categories crosscut saw kerf volume loss (0.24%, RS<1MM), stump volume loss for motor-manual felling (1.26%), top volume loss (3.7%, <1MM) and total volume loss (10.09%, <1MM). With incorrect log trimming allowance allocation volume loss, which was not related to compt. vol., roadside felled mechanical operations produced the greater volume loss percentage (1.29%). The following sections will elaborate on particular volume losses as they occurred in the study.

Although no supporting literature could be found apart from that of Favreau (1997) and Araki (1996) when referring to the causes of volume losses occurring in harvesting operations,

Table 5: Logs (%) over- and under-scaled during merchandising

	Roadside log scaling		Merchandising yard log scaling	
Over scaled (%)	2.73[a]		2.37[a]	
Under scaled (%)	2.07[a]		6.87[b]	
	Compt. vol. <1 m^3	Compt. vol. >1 m^3	Compt. vol. <1 m^3	Compt. vol. >1 m^3
Over scaled (%)	2.41[a]	2.80[a]	3.00[b]	1.56[c]
Under scaled (%)	2.09[a]	2.12[a]	11.78[b]	0.58[c]

Table 6: Simsaw6 simulation results

Merchandising location	Log volume (m^3)	No. of logs (sawlogs)	Product value (R)	Gross value recovery (R m^{-3})	Net value recovery (R m^{-3})	Average log cost (R m^{-3})
Merchandising yard	59.391	285	79 108.50	1 331.99	936.13	395.86
Roadside	61.515	300	80 994.06	1 316.65	927.22	389.44

Table 7: Lost opportunity costs: additional area and volume felled to replace losses, lumber value and log value not recovered

Category	Wood utilisation (%)	Additional volume (m^3)	Additional area (ha)	Net lumber value not recovered (million R)	Log value not recovered (million R)
Overall total volume loss	92.068	421 722	1278	392.847	165.564

the authors are of the opinion that most volume losses could be human related and not system related and that most of the volume losses quantified can be negated through workers and supervision applying their training and skill.

Excessive stump heights and stump volume loss

Over all treatments, stumps are cut on average 7.0 cm above an acceptable felling height, as defined in the study. Statistical analysis showed that the percentage volume loss related to stumps in motor-manually felled trees for compt. vol. < 1 m^3 exceeded those of mechanised felled trees of the same size, and motor-manually felled trees of compt. vol. > 1 m^3 (1.26% vs 0.07% and 0.58%) (Figure 2a). There was no significant difference in percentage volume losses because of felling method among larger felled trees (0.67%). Mechanised felling of larger trees produces more volume loss than mechanically felled smaller trees (0.79% vs 0.07%). Mechanical felling has been shown to be beneficial for lower stump volume losses in this study, but that motor-manual felling, if correctly applied, can produce the lowest stump volume loss because of choices that can be exercised by a well-trained chain saw operator with the right attitude towards the work.

As trees become larger, and their butt flares become more accentuated, felling cuts are forced higher than would be the case with trees with no butt-flares. The present study does not reflect this proposed logical trend. The reason for this can be attributed to the emphasis on felling production at the cost of safe and correct felling techniques. The practice of clearing down to the mineral soil around stumps before felling is generally not applied and harvesting sites typically exhibit high stumps. However, the study also shows that in larger compt. vol. trees there is no difference in volume losses between motor-manual and mechanised felling methods (Figure 2a). There is agreement in the international literature, such as Murphy and Olsen (1988), Warkotsch (1988), Kewley and Kellogg (2001), and Han and Hall (2006), on two points. Firstly, high stumps and wide saw kerfs are a major contributor to timber loss not only in the preparation of the tree but in the ensuing extraction process and, secondly, that motor-manual felling generally results in greater fibre loss than mechanised felling (e.g. the use of feller-bunchers). In general, mechanical felling produced the lowest stump volume losses, which are potentially influenced more by girth at felling height than the actual compt. vol. of the trees.

Felling saw kerf volume loss

Figure 2b indicates that mechanised felling with disk saws produces significantly greater levels of felling saw kerf volume loss than motor-manual chain saw felling. The difference between motor-manual and mechanical felling is not entirely unexpected because of saw kerf widths of a chain saw chain and the disk saw. Motor-manual felling, as opposed to mechanised felling, produced similar volume losses regardless of compt. vol. (0.15%), but there was a significant trend of reduced loss as compt. vol. increased (Figure 3b). Mechanised felling produced greater fibre losses, which decreased significantly as compt. vol. increased from <1 m^3 to >1 m^3 (1.0% and 0.88%) (Table 4, Figure 3a), as opposed to motor-manual felling in compt. vol. < 1 m^3 and > 1 m^3 (0.15%) (Table 4, Figure 3b). Fibre loss can be significant between disk saws and chainsaw for felling. By using the 0.15% loss for motor-manual felling and a weighted average of 0.92% for mechanised felling, it is calculated that fibre losses for a chain saw felling kerf equates to 7 350 m^3 (19.7 ha of plantation) and mechanised felling 45 400 m^3 (122.0 ha of plantation).

By reducing saw kerf to 0.8 cm, the same volume can be produced while felling 38 000 m^3 less volume. However, as found in this study, mechanised felling in general produced lower stumps and subsequent lower stump volume losses.

Mechanised felling could also somewhat negate the potential benefit of a narrower saw kerf. Nevertheless, a major concern is the safety of chain saw operators and mechanised felling does presents a number of operational and social opportunities compared to motor-manual felling, particularly in terms of improved safety (taking the man off the forest floor), higher production (felled m^3 PMH^{-1}), and the bunching of stems to ease primary transport to roadside; all factors are supported by Carey and Murphy (2005).

Log trimming allowance volume losses

Although the allocation of up to a 10 cm log trimming allowance is required by policy on every sawlog assortment produced in South Africa for reasons of final product recovery by sawmills, it makes a considerable contribution to volume losses. The average weighted volume loss related to the log trimming allowance over all treatments was 1.62%. Using the parameters as above this relates to 80 600 m^3 or 244.3 ha of additionally felled trees to reach the required volume. Statistically, stems, regardless of compt. vol., merchandised at roadside and felled mechanically produce the highest percentage loss of 1.84% (Table 4, Figure 3c), as compared to those merchandised at merchandising yards (1.66% and 1.26% (MY>1m^{3}Mech)) (Table 4). With roadside merchandising, mechanised felling produced significantly greater losses to that of motor-manually felled trees irrespective of tree size (1.84% vs 1.47%) (Table 4, Figure 3c). With merchandising-yard merchandising, compt. vol. and felling method seemed to have a role in volume loss. As compt. vol. increased the volume loss due to log trimming allowance deceased, but only with MY>1m^{3}Mech (1.66% vs 1.26%) (Table 4, Figure 3d).

These differences are more difficult to explain and there are no similar experiences from the international literature to support this occurrence. There are two effects that might be relevant in the case of log allowance volume loss. Firstly, both Warkotsch (1988) and Kewley and Kellogg (2001) suggest that mechanised felling produces fewer stem breakages than motor-manual felling. At roadside merchandising, mechanically felled trees are more intact (Kewley and Kellogg 2001) and potentially produce more assortments, hence increased log allowance losses. The opposite could be true for motor-manually felled trees. However, the weighted mean for log trimming allowance volume loss between roadside and merchandising-yard merchandising (but not taking into account the mechanically felled compt. vol. >1 m^3 destined for merchandising yard processing) is almost the same at 1.66%. The exception was with extremely large trees (1.45 m^3 stem^{-1}) (Table 4), which produced fewer but longer logs and hence reduced log allowance (1.26%).

The other issue is the difference between roadside and merchandising-yard merchandising work. Merchandising yard operations resemble frenetic activities where unevenly spaced, large volumes of tree-length deliveries require immediate scaling and crosscutting. At roadside operations, it is the opposite; there is more time for more accurate scaling decisions to be taken.

Incorrect log trimming allowance allocation volume loss

Across all treatments the weighted average volume loss related to the incorrect log trimming allowance allocation is 0.60%, which equates to 29 500 m^3 and 90.0 ha of additional resource that is felled to produce the volumes required (Figure 2g). Although there was no difference between motor-manual felling at either roadside or merchandising yard (0.45%), there was a significant difference for trees felled mechanically and merchandised at roadside as compared trees mechanically felled and merchandised at merchandising yards (1.29% vs 0.24%). A possible explanation for this divergence of volume recovery between roadside and merchandising yard log-scaling could have its basis in the manner in which, particularly the extracted stems, are presented for the log-scalers. At merchandising yards, all stems arriving at the yard are normally decked onto skids and separated from one another (stems are spaced) making it easier for both the scalers and crosscutters to access individual stems. The opposite is true for roadside operations where stems are generally not placed on skids or purposely separated from one another before the scaling starts. The problem is aggravated by grapple skidding as opposed to cable-skidder skidding. Grappled stems are normally decked tighter and over one another than stems that are cable skidded. Cable-skidded stems normally need to be separated to facilitate dechoking; this facilitates the next operation in the sequence. Although not generally used, apart from in some areas of the Western Cape, skids at roadside can add significant value because the stems are elevated and hence off the ground and separated. Although this elevation is not quite as high as at merchandising yards, it does provide some benefit. This facilitates access for the log scalers and chain saw operators to begin crosscutting the tree-lengths.

A further point that arose during the study, and which is related to the allocation of the log allowance, was the percentage of logs both under- and over-measured during log scaling (Table 5). Under-scaling a log results in the log being relegated to the next lower log-length class, and the piece of wood between this class and the actual log-length removed and discarded once the boards reach the board mill. Over-measuring has a similar result in that the piece of wood not required by the mill is then discarded. In both cases under- and over-measurement was most prevalent at merchandising yards, with smaller trees over- and under-measured showing the highest percentage loss and larger trees over-and under-measured showing the lowest percentage (Table 5). In both cases there was no difference for both the smaller and larger trees at roadside merchandising. This points to suboptimal execution of an all important task such as log scaling and, as stated by Murphy and Olsen (1988), improved fibre recovery is based in carefully planned log scaling and/or by moving merchandising to another location (e.g. from roadside to merchandising yards). Although the first point made by Murphy and Olsen (1988) is clearly of importance, but not applied in South African operations, the second point is not entirely supported by the outcomes of the present study.

The use of merchandising yards in their current form and management, as with most other harvesting operations, most certainly needs some intervention in terms of the supervision of log scalers. In addition, the use of skids is recommended for roadside merchandising operations.

Furthermore, by improving worker practices and the use of mechanised CTL technology, with related precision crosscutting technology available, this allowance can be either reduced or removed entirely. Some sawmills in South Africa now require a minimum of 10 cm per log purely because there is no guarantee to the quality of the dimension the mill will receive as a result of poor log scaling and crosscutting work. A point that must be made, and it is unsure if this is understood in the industry, is that as long as the mill gets the required length from which to cut a final board optimally, no additional wood is required; longitudinal shrinkage is minimal. Instead of rigorously applying 10 cm, and in some cases >10 cm, rather practice precision crosscutting mechanically (or motor-manually) and reduce wasted fibre.

Cross-cut saw kerf volume losses

The average weighted volume loss for the study related to crosscut saw kerf is 0.20% and is equivalent to 9 800.0 m^3 and 30.0 ha additional volume and plantation area that needs to be felled to maintain annual volume supply. The greatest volume loss percentage occurred with the RS<1MM treatment (0.24%), in addition roadside merchandising had greater volume loss than merchandising-yard merchandising (0.17%). There was also a difference at roadside merchandising between compt. vol. < 1 m^3 for mechanical and motor-manual felling (Table 5) (0.20% vs 0.24%), but there was no difference for merchandising yards between compt. vol. and felling methods (0.17%). The differences found at roadside merchandising operations are not influenced by compt. vol. (Figure 3e and f). Once again these differences are difficult to explain and there are no similar experiences from the international literature to support this occurrence. The differences are only related to one aspect of the trees of compt. vol. < 1 m^3 felled mechanically and merchandised at roadside and can be ascribed to perhaps an inordinate larger number of logs produced in this treatment, i.e. in smaller trees and poor log-scaling practices.

Top volume losses

There is no significant difference for top volume losses; i.e. merchantable pieces left in-field after breakages from felling or the primary transport, between felling method and tree size for larger compt. vol. However, for smaller compt. vol., motor-manual felling (3.70%) had significantly higher volume losses than trees of the same size mechanically felled (2.09%) (Figure 2e). This is most likely because of breakages occurring during skidding of the long slender stems. In other cases (compt. vol. > 1 m^3) stems are more rigid (stronger) and/or bunched, thus protecting against undue breakages. In total, top volume losses amount to 2.57% (weighted average), which is equivalent to 129 000 m^3 or 391.0 ha of additional plantation that would be required for the same volume production. Murphy et al. (1991), Gingras (1992), Favreau (1997) and FERIC (2004) concur with findings in this study as far as timber breakages reported in this study are concerned, although the fibre recovery noted by Gingras (1992) could not be replicated in this study, even though felling to lead and felling directionally will have definite advantages.

Excessive trimming and removal of merchantable wood volume loss

The weighted average mean of this volume loss factor is 2.02% of the total merchantable volume available and equates to 100 900 m^3 or 305 ha of plantation. There was no difference between treatments in operations at merchandising yards but with roadside merchandising there was greater volume loss for trees motor-manually felled regardless of compt. vol. (1.56% vs 0.48%).

In general, it was found that log scalers would err on the side of overcautious when making decisions around the removal of wood defects, hence long lengths of good wood is taken out at the same time. The reason may be that if no-one quantifies, and hence questions, the amount of good wood left in-field (as in the current scenario), there is no point running the risk of reprimand for possibly producing a log with a blemish because of more circumspect removal of defects. Once again the rushed activities at merchandising yards may play a role in the greater volume loss at merchandising yards (2.47%). Log scalers will also not return to previously scaled stems to check on the result of the scaling decision to learn the attributes of various defects and how they could in future react or plan their log scaling.

Fibre value and cost

The simulation of sawlogs assortments produced at roadside and merchandising yards, in terms of net value recovery (after log cost is taken into account) revealed a difference of R8.00 m^{-3} (R927.22 m^{-3} vs R936.13 m^{-3}) for the volume of the sawlog sample produced (61.515 m^3 vs 59.391 m^3) at either location (Tables 6 and 7). The total value recovered for sawlogs produced at roadside and at merchandising yards was R80 994.06 and R79 108.50, respectively, with an associated average sawlog cost of R389.44 m^{-3} and R395.86 m^{-3}. The SIMSAW 6 simulation revealed essentially the same outcomes (value recovery and average log cost) between roadside and merchandising yard log-scaling activities, which indicated the same levels of training of log scalers. If, however, these log scaling decisions were the optimum, remains to be investigated in a future study.

In the present study, SIMSAW 6 predicted a weighted average net recovery value of R931.53 m^{-3} for the total volume of logs produced and the weighted average cost of logs, which the plantations can expect in revenue when selling logs to the mill, of R392.59 m^{-3}. Based on the total volume of wood not recovered because of the volume losses, the revenue thus lost is R392.847 million m^3 y^{-1} in board products and R165.564 million m^3 y^{-1}in roundwood supply from plantations. The base assumption is an average annual roundwood delivery of 4.895 million m^3 y^{-1} and based on the total volume loss of 7.932%.

Conclusion

A study of both fibre balance and fibre cost was done across the South African softwood sawtimber industry to gain information on the actual utilisation of useful fibre and the potential loss/gain of opportunity in terms of cost and revenue from both field practices and policy (log allowance). The study quantified volume losses from high stumps, felling and crosscut saw kerf, log allowances, excessive removal of merchantable wood, incorrect log allowance allocation, and leaving utilisable wood in-field. The study followed eight separate treatments of which four terminated with merchandising at roadside landing and four at merchandising yards. In the treatments felling method was by either motor-manual or mechanised and compartments were classed based on average compartment tree size class (less than or greater than 1m^3). Results of the study show a significant amount of utilisable fibre is being lost or discarded during the timber harvesting and merchandising operations in the South African softwood saw timber industry.

On average, across all treatments 7.932% of total utilisable tree volume is being lost as fibre. This equates to 421 722.42 m^3 of lost volume to the industry or 1 277 ha of additional plantation that needs to be felled to meet mill requirements. The study found that merchandising location had no bearing on the final outcome of volume lost but that roadside operations, for trees <1 m^3, provided the greatest loss of useful fibre.

Motor-manually felling across the board caused greater volume losses when compared to mechanised felling and hence serious consideration should be given to the mechanisation of the felling process in harvesting operations, or that chain saw operators be controlled to deliver the product of work required of them. Apart from wide saw kerfs, mechanised felling offers a number of benefits such as enhanced safety through removing the man from the forest and greater production per productive machine hour.

The 10 cm log allowance expected on all sawlogs by policy, currently consumes approximately 80 604 m^3 of wood annually. This allowance is discarded once the product is removed and serious consideration must be given to how this requirement is controlled. Nevertheless, as long as supervisors, log scalers and chain saw operators continue to produce substandard work, there is no other solution but to ensure that at least 10 cm of allowance be added to each log. With regard to fibre cost, a SIMSAW 6 simulation based on the total volume of wood not recovered because of the volume losses found, revenue lost is R392.847 million y^{-1} in board products and R165.564 million y^{-1} in round wood supply from plantations.

The study has in principle confirmed what is stated in the international literature that significant amounts of fibre is being lost because of poor harvesting and transport practices not only in South Africa but worldwide. The study suggests that the human impact on the efficient and effective utilisation fibre lost is far greater than effects of the individual components within the harvesting system itself. The impact of training on fibre losses were not part of the study and as such cannot be taken as fact. However, it goes without saying that training of personnel, adequate harvest planning, implementation and control of operations are imperative to ensure supply and value chain goals are met. However, further work is required to determine the impact of either human or systems decisions on the effective utilisation of fibre.

Acknowledgements — The authors would like to acknowledge the South African sawtimber industry for making their plantation available for field work related to this study. The authors acknowledge the input of a number of UBC exchange students that assisted in data collection. In particular, the authors would like to acknowledge Elizabeth Gleasure for her significant input into the field work and analysis of the results of the study.

References

Araki DS. 1996. Increasing value and fibre recovery from coastal forests by manufacturing longer logs. *FERIC Technical Note* no. 247. Vancouver: Forest Engineering Research Institute of Canada.

Bilborough A. 2008. Waste assessment: line intercept method. Forest Resource Optimisation Field Note. Pietermaritzburg: Mondi Group.

Bredenkamp BV. 2000. Volume and mass of logs and standing trees. In: Owen DL (ed.), *South African forestry handbook*, vol. 1. Pretoria: South African Institute of Forestry. pp 167–175.

Carey P, Murphy G. 2005. Mechanised versus manual log-making in two Chilean *Pinus radiata* stands. *New Zealand Journal of Forestry Science* 35: 24–34.

Erasmus D. 1994. National terrain classification for forestry. Compiled on behalf of the National Terrain Classification Co-operative. *ICFR Bulletin Series* no. 11/1994. Pietermaritzberg: Institute for Commercial Forestry Research.

Favreau J. 1997. A comparison of fibre loss during full tree and cut to length harvesting. *FERIC Technical Note* no. 118. Pointe Claire: Forest Engineering Research Institute of Canada.

FERIC (Forest Engineering Research Institute of Canada). 2004. Reducing breakage during skidding and delimbing. Available at http://www.feric.ca/index.cfm?objectid=4B27D8EA-B918-5739-EB203EC19E296A3A [accessed 7 February 2008].

FSA (Forestry South Africa). 2009. Abstract of South African forestry facts for the year 2007/2008. Rivonia: Forestry South Africa.

Gingras J-F. 1992. *Fibre recovery efficiency of wood harvesting systems*. *FERIC Technical Note* no. 186. Pointe Claire: Forest Engineering Research Institute of Canada.

Ham C, Ackerman PA, de Wet J, du Toit B, Geldenhuys C, Ham H, Howard M, Mortimer J, Seifert T, Wessels B. 2010. Saw log strategy and implementation plan for South Africa. Report submitted to Department of Agriculture, Forestry and Fisheries. Stellenbosch: Stellenbosch University.

Han H-S, Hall R. 2006. Improvements in value recovery through low stump heights: mechanised versus manual felling. *Western Journal of Applied Forestry* 21: 33–38.

Kanawaty G (ed.). 1992. *Introduction to work study* (4th edn). Geneva: International Labour Office.

Kewley S, Kellogg L. 2001. Mechanical feller-buncher felling: an example study on timber value recovery in South Africa. *Southern African Forestry Journal* 192: 59–63.

Milton JS, Arnold JC. 1999. *Introduction to probability and statistics: principles and applications for engineering and the computing sciences* (2nd edn). New York: McGraw-Hill.

Murphy GE. 2003. Worldwide experiences with mechanization and value recovery. In: *Proceedings of the Wood for Africa 2002 Conference, July 2002, Pietermaritzburg, South Africa*: pp 22–32.

Murphy GE, Cossens GP, Twaddle AA. 1991. How to improve value recovery from plantation forests: research and practical experience in New Zealand. In: McNeel JF, Andersson B (eds), *Forestry operations in the 1990's, challenges and solutions: proceedings of the 14th Annual Meeting of the Council on Forest Engineering, 22–25 July 1991, Nanaimo, British Columbia, Canada.* Tahoe: Council on Forest Engineering. pp 30–38.

Murphy GE, Olsen G. 1988. Value recovery from trees bucked on a landing and at a stump. *Forest Products Journal* 38(9): 49–52.

Ride K. 1999. An investigation of wood fibre recovery and related economics of four harvesting systems common to Northwestern Ontario. MSc (Forestry) thesis, Lakehead University, Canada.

Shaffer MR. 1992. A comparison of sheared and saw-head-felled stump heights on six nonindustrial private timber sales in South-Eastern Virginia. *Southern Journal of Applied Forestry* 16: 140–142.

von dem Bussche GH. 1987. Specifications for softwood saw- and veneer logs. In: Von Gadow GH, van der Zel DW, van Laar A, Schänau APG, Kassier HW, Warkotsch PW, Vermaas HF, Owen DL, Jordaan JV (eds), *South African Forestry Handbook*. Pretoria: Southern African Institute of Forestry. pp 384–389.

Warkotsch WP. 1988. The effects of harvesting on timber quality. *South African Forestry Journal* 147: 53–62.

Wessels CB, Price CS, Turner P, Dell MP. 2006. Integrating harvesting and sawmill operations using an optimized sawmill production planning system. In: Ackerman PA, Längin DW, Antonides MC (eds), *Precision forestry in plantations, semi-natural and natural forests: proceedings of the International Precision Forestry Symposium, 5–10 March 2006, Stellenbosch University, South Africa*. Stellenbosch: Stellenbosch University. pp 341–349.

Young G. 1998. Mechanical and manual log manufacturing in coastal second-growth forest: a comparison of recovered value. *FERIC Technical Note* no. 267. Vancouver: Forest Engineering Research Institute of Canada.

Erratum

Readers should be aware prior to reading the following paper (Fibre volume losses of eight softwood clearfell harvesting systems in South Africa) of an error in the abstract.

This correction applies to the sentence beginning on line 9 and reads as (the incorrect segment is bolded):

*"Stumps were found to be 7 cm higher than necessary and volume losses because of high stumps were **0.79% and 0.07% for mechanical and motor-manual felling, respectively**."*

While stumps were found to be 7 cm higher than necessary, the volume losses associated for mechanical and motor-manual felling were in fact also dependent on average compartment volume. For compartments averaging less than 1 m^3, motor manual felling average stump losses were 1.26% and mechanical losses were 0.07%. For compartments averaging greater than 1 m^3, motor manual felling stump losses were 0.58% and mechanical felling were 0.79% respectively. When average compartment tree volume is excluded and the sample sizes for each group are considered, the average stump volume losses for motor manual felling was 0.81% and for mechanical felling 0.43%. This statement should therefore replace the above bolded sentence.

Southern Forests 2014: xx–xx
Printed in South Africa — All rights reserved
This is the final version of the article that is published ahead of the print and online issue

Copyright © NISC (Pty) Ltd
SOUTHERN FORESTS
ISSN 2070-2620 EISSN 2070-2639
http://dx.doi.org/10.2989/20702620.2014.917355

Chapter 4: Modelling of wander ratios, travel speeds and productivity of cable and grapple skidders in softwood sawtimber operations in South Africa

Pierre Ackerman[1*], Reino Pulkki[1,2] and Elizabeth Gleasure[1]

[1] *Department of Forest and Wood Science, Stellenbosch University, Stellenbosch, South Africa*
[2] *Faculty of Natural Resources Management, Lakehead University, Thunder Bay, Ontario, Canada*
** Corresponding author, e-mail: packer@sun.ac.za*

The objective of this study was to develop predictive models for cable and grapple skidder wander ratios, travel speeds (loaded and unloaded), and productivity in softwood roundwood sawtimber harvesting operations. For field data collection, the study utilised on-board computing systems supported by manual time study. Four-hundred and twenty-seven extraction cycles over varying terrain and tree sizes were studied for 13 sites in the Western, Southern and Eastern Cape, and KwaZulu-Natal. Machine make and model as well as gross power rating were studied. Due to insignificance across skidder types and configurations, the objective of creating a predictive model for skidder wander ratio was not met. The overall mean wander ratio for all skidders and terrain studied was 1.12:1. This value was used in the models subsequently developed. No differences were found for unloaded and loaded travel speeds between individual skidder types and speeds were found to be 7.3 km h^{-1} and 5.5 km h^{-1}, respectively. In terms of productivity, when based on field-measured data, there were differences between skidder types with cable skidders achieving 43.9 m^3 per productive machine hour (PMH) and grapples skidders 123.9 m^3 PMH^{-1}. The study, however, found that both cable and grapple skidders were only hauling approximately 50% of their capacity and for that reason multiple regression models to predict potential production at full payload capacity were developed for the two skidder configurations. Multiple regression was also used to develop prediction models for travel speeds loaded and unloaded. The study met its objectives for driving speeds and productivity, and the developed models will be used in a subsequent network analysis to provide solutions to optimise the softwood sawtimber supply chain. The study also found that the human element had an impact on the factors studied and that good training, planning, implementation and operational control are imperative to ensure supply (or value) chain goals are met.

Keywords: primary transport, productivity, skidder travel speeds, wander ratio

Introduction

The South African industrial plantation forests cover about 1.2 million ha, producing in excess of 18.5 million m^3 a^{-1} of roundwood of which 4.5 million m^3 is softwood sawtimber (FSA 2011). Across the industry different ground-based harvesting systems are used to extract this sawtimber to roadside with the skidder being a popular choice in both soft- and hardwood sawtimber operations on slopes generally less than 20% (Warkotsch 1988). Although grapple skidders tend to have higher productivity (Kluender et al. 1997) and are becoming increasingly popular, cable skidders are currently more commonly used in the South African forest industry.

Developing predictive models for skidder wander ratios, travel speeds and productivity is the goal of this study as these outcomes will be utilised in a future softwood sawtimber supply chain simulation study. The following literature review concentrated on these three variables, as well as the potential influence of terrain. The effect of power rating, skidder type (cable or grapple) and machine mass on potential (or full) skidder payload were also reviewed.
A literature search revealed no studies specifically concerned with determining skidder speeds; however, speed was examined as a component of time consumption and productivity (Kluender et al. 1997; Odhiambo 2010; Mousavi 2012a, 2012b). In a time study investigation of skidder operations by Kluender et al. (1997) under varying harvesting strategies using both cable and grapple skidders either individually or in combination, cable skidders were found to have slower travel speeds in both the loaded and unloaded directions.

Odhiambo (2010) studied a Clark Ranger H67 cable skidder extracting tree-lengths in a softwood plantation in South Africa. Average speed unloaded was found to range from 6.0 to 7.0 km h^{-1} and from 3.7 to 4.2 km h^{-1} in the loaded direction. Mousavi (2012a) found average travel speeds of a Timberjack 450C cable skidder loaded and unloaded to be 5.9 km h^{-1} and 5.8 km h^{-1}, respectively. Mousavi (2012a) found that time consumption for travel loaded depended on the number of pieces (long-logs or tree-lengths), payload and skidding distance. Mousavi (2012a) also noted that average time consumption for travel unloaded was largely the same as travel loaded, and that time consumption for travel unloaded depended on the skidding distance and longitudinal slope. In this context and with the same skidder in a follow-up study, Mousavi (2012b) found travel unloaded speeds averaged 5.7 km h^{-1}

and travel loaded speeds were faster ranging from 6.2 to 7.7 km h^{-1}. Mousavi (2012b) found that the change in speed can be attributed to the adverse slope in the travel unloaded direction and that productivity was highly dependent on skidding distance.

Although no specific reference could be found for grapple skidders and average travel speed, Hogg et al. (2010) developed two regression models to predict travel loaded and unloaded speed of a Tigercat 630C grapple skidder in a multistem eucalyptus pulpwood operation for input into a simulation model. For both directions, extraction distance was the only significant variable.

The effect of the skidder's power on speed has also not been directly studied, although it has been examined in the context of optimal payload and productivity by Curro and Verani (1990), Colton and Brink (1999) and Egan and Baumgras (2003). Curro and Verani (1990) calculated the optimal payload for a Timberjack 380 grapple skidder based on the skidder's weight, tractive force, rolling resistance and extraction distance in order to maximise productivity during a *Pinus radiata* D.Don first thinning. They determined optimal productivity for an extraction distance of 100 m would be achieved with a payload of 8.18 m^3 resulting in a maximum productivity of 77.1 m^3 per product machine hour (PMH). Speed is described from a linear regression equation developed from their empirical data and uses payload volume as the only predictor; however, travel speed itself is not specifically discussed and the emphasis is instead placed on determining productivity.

Building on the work of Curro and Verani (1990), Colton and Brink (1999) calculated the optimal payload for a Timberjack 380C cable skidder using a variety of methods including FAO (1977), Curro and Verani (1990) and Spong (2001). They used 8.5 m^3, calculated by the SkidPC method (Spong 2001) as a baseline and then tested this figure in-field. They found the relationship between the payload size, travel loaded speed and terminal times (choking and dechoking) was not significant. The influence of the unloaded travel component was not discussed. Although the data was unclear regarding the mean travel speeds, in the unloaded direction speeds ranged from 3.7 to 10.1 km h^{-1} and from 2.4 to 4.9 km h^{-1} in the loaded direction. Egan and Baumgras (2003) found no significant interaction between skidder size and trees per cycle; however, skidding distance was a significant predictor of productivity. Furthermore, they also found that the travel unloaded cycle was the most variable, possibly due to the operator searching for and planning the next turn of timber.

Terrain aspects including slope, soil conditions and ground roughness may influence an operator's decision of where to drive; he/she may select a winding rather than straight line path (Terlesk 1983; Davis and Reisinger 1990). Physical obstacles are created by microtopography and contribute to the resistance forces acting on the skidder (Suvinen et al. 2003; Tiernan et al. 2004). While there would be no change in energy for a single wheel going over an obstacle, for the machine as a whole there is a loss of energy known as obstacle resistance (Marklund 1987; Suvinen et al. 2003).

Slope will affect the speed and stability of a machine used for timber extraction (Davis and Reisinger 1990). It will also influence the location of roads and consequently the distance travelled from stump to roadside (Terlesk 1983; Tiernan et al. 2004). Poor soil conditions associated with ground strength are important because they affect machine productivity and the potential of machine-inflicted environmental damage (Davis and Reisinger 1990; Saarilahti 2002; Suvinen et al. 2003; Tiernan et al. 2004).

Tiernan et al. (2004) found that in areas where terrain conditions were classified as easy for timber extraction, machine productivity was higher for all extraction distances and payload sizes. However, for sites that were difficult, optimising payload size and extraction distance was significantly more important (Tiernan et al. 2004). Davis and Reisinger (1990) found that site-specific terrain factors should be taken into account in the initial harvest planning stage to ensure maximum productivity of the equipment used for timber extraction and to avoid inefficiencies from poor harvest planning. Alternatively, Davis and Reisinger (1990) found that high-resolution geographic information system (GIS) data can be used to map out descriptive terrain characteristics to improve the efficiency of harvest planning and reduce the likelihood of inefficient, primary transport routes.

A global positioning system (GPS) has been found to be effective in collecting information to map out the path of a skidder or to determine the optimal off-road machine route (Cordero et al. 2006; Suvinen 2006; Pellegrini et al. 2013). In fact, the use of GPS greatly improves the accuracy of GIS analysis compared to a model created using only field surveys (Cavalli et al. 2006). Kopka and Reinhardt (2006) and Folegatti (2010) collected machine operating hours and GPS data from skidders using Multidat dataloggers, calculated actual distances travelled using ArcMap, and found the average actual travel distance is greater than average shortest (straight line) distance or path (i.e. wander ratio). This difference in distances can be related to factors such as slope, soil strength and ground roughness, or even the level of the initial harvest planning.

According to Kopka and Reinhardt (2006), the accuracy of a satellite navigation system when under optimal conditions can determine the off-primary transport route to an accuracy of 10%, with the GPS signal itself being accurate to 5 m as of 2005. Advancing to 2013, Pellegrini et al. (2013) used an on-board computer system (OBC), equipped with GPS, to evaluate the use of OBCs in the South African forestry context. Their GPS errors were typically less than 5% and this was considered an acceptable level of accuracy.

From the literature reviewed, no specific information was available for wander ratios, travel speeds for either cable or grapple skidders or the effect of wander ratios on the travel speeds for these skidder types. This information depends largely on local conditions and how a harvest plan is implemented and would hence be regionally specific, which matches the objective of this study. Potential productivity, determined by approximate optimal machine payload, is less understood but can provide some insight into the utilisation of individual machines and their capabilities. Developing predictive models for wander ratio, skidder speeds (both unloaded and loaded) and productivity (both field-measured and potential) in a South African context was the main objective of this study as these models will be utilised in a future softwood sawtimber supply chain simulation study.

The objectives will be achieved utilising OBC systems supported by time studies. The limitations of the study were:

- only articulated skidder extraction systems were evaluated
- the study is limited to softwood sawtimber operations between the stump site and roadside landings
- extraction is limited to tree-length and full-tree extraction.

Materials and methods

Study areas

Study sites were selected from pine sawtimber plantations of the Western, Southern and Eastern Cape, and KwaZulu-Natal. Predominant species harvested were *Pinus radiata*, *P. elliottii*, *P. patula* and *P. pinaster* in sawlog production (Table 1). Thirteen individual extraction operations were studied and included two skidder extraction systems where timber was extracted to roadside landing. The systems were (1) motor-manual felling and tree-length extraction by cable skidder, and (2) mechanised (feller-buncher) felling and grapple skidder extraction of full-trees to roadside landing. Cable skidders were used in both the Western and Southern Cape and grapple skidders were used in the Southern and Eastern Cape and KwaZulu-Natal. It was not possible to replicate grapple skidders in the Western Cape or cable skidders in KwaZulu-Natal and the Eastern Cape. It was also not possible to replicate manufacture type and gross power rating (kW) due to availability of systems and/or machines.

Trees were debranched and topped motor-manually in field before extraction to roadside landing for the cable skidder system. For the full-tree system, trees were extracted to roadside where they were debranched. Trees were skidded butt-first to roadside. Log scaling and cross-cutting of stems into assortments occurred at roadside landing; cross-cutting was motor-manual. All operators (machine drivers, log scalers and chainsaw operators) were considered trained and experienced with the task they were involved in.

In-field data collection

Data collection was completed using a combination of an OBC (MultiDAT) equipped with a GPS and through manual time studies. The GPS hardware (MultiDAT) and its accompanying software were made available by FPInnovations of Canada and had been used in previous skidder time studies (Pellegrini et al. 2013). Manual time studies were conducted using WorkStudy+™ 3.0 on a hand-held computer. Each element was timed using this software. The skidding cycle was divided into the following four elements: travel unloaded, loading (choking or grappling), travel loaded and unloading (dechoking or releasing grappled) at roadside landing. Operational and mechanical delays were not taken into account. Along with element times, the number of full-trees or tree-lengths skidded per cycle, average tree volume, machine type, gross power rating (kW) and average slope for the extraction area were recorded.

Data manipulation and ArcGIS

Global positioning system points were assigned to their corresponding element. In-field extraction distance was defined as the sum of the distance between the travel loaded (element 3) points for a given cycle. Straight line extraction distance was defined as the shortest straight line path from the loading point (element 2 – travel loaded) to the roadside landing where unloading took place. Loading was defined as time spent gathering load; travel loaded time therefore happened after the entire load had been acquired. The wander ratio was defined as the quotient of the infield extraction distance (travel loaded) to the straight line extraction distance (travel loaded).

Table 1: Summary of short-form codes for individual skidder models

Skidder model	Code
Timberjack 380C	TJ380Cable
John Deere 640G III	DG640Cable
Clark Ranger H67	CR67Cable
Tigercat 625c	TC625Grapple
Bell 648GIII	BL648Grapple

Speed was calculated as the weighted average speed based on the distance between GPS points for the unloaded and loaded directions for each cycle. Manual recordings of the number of trees per cycle and compartment enumeration data provided were used to calculate the payload volume and productivity of each cycle. For analysis purposes data was allotted according to skidder type rather than specific operations or operator and skidder types were assigned short codes for easier identification (Table 1).

Terrain conditions are described in Table 2, and are based on the National Terrain Classification System for Forestry (Erasmus 1994). Data collection occurred during fine weather to facilitate time study data collection. In order to reduce complexity, and for later discussion purposes, terrain conditions were converted to a single (risk) factor, in accordance with MacDonald (1999), for each extraction route traversed by each skidder in each study site. The risk-levels described by MacDonald (1999) are numbered 1 to 6 (minimal risk to areas not recommended for ground-based harvesting equipment). Slope was determined in the direction of travel loaded; i.e. (−) down-slope and (+) up-slope, and a general slope was assigned to each extraction route.

Maximum or potential skidder payload was calculated using methods described in the *Planning Forest Roads and Harvesting Systems* FAO Forestry Paper no. 2 (FAO 1977). As the terrain across skidding sites was consistently firm, dry ground, a tractive coefficient of 0.55 was used. In order to convert between volumes and mass, the *South African Forestry Handbook* softwood density conversion factor of 1.06 t m^{-3} was used (Bredenkamp 2000).

Potential optimal haul capacity (payload) should be viewed as theoretical because a number of factors, such as diameter at breast height, piece length, choker capacity on the mainline and butt plate area on cable skidders to receive tree-lengths, affect this capacity. Others factors such as felling direction, choker setter ability, worker supervision and general harvest planning will largely determine the achievability of such a ‘potential’ payload. The calculation, however, does allow for comparison when comparing field measured and predicting (potential)

Table 2: Number of cycles measured by skidder type, configuration and study site number

Study site	Cable			Grapple	
	TJ380Cable	CR67Cable	DG640Cable	TC625Grapple	BL648Grapple
Skidder code	TJ380	CR67	DG640	TC625C	BL648
Gross power rating (kW)	113	138	128	164	128
Western Cape (*N* = 207)					
Study sites: 1, 2, 6, 9	*N* = 104	*N* = 25			
3	*N* = 45				
7	*N* = 33				
Southern Cape (*N* = 105)					
Study sites: 10, 11	*N* = 30				*N* = 34
12	*N* = 23				
13			*N* = 18		
Eastern Cape, KwaZulu-Natal (*N* = 115)					
Study sites: 4, 5				*N* = 51	
8				*N* = 64	
Total *N*	235	25	18	115	34
	278			149	

productivity. For productivity comparisons in-field extraction distance across skidder types was standardised to provide appropriate comparison.

Statistical analysis

Statistical analysis was performed using STATISTICA 11 software (StatSoft, Tulsa, Oklahoma, USA). One-way analyses of variance (ANOVAs) were performed for the variables of wander ratio, speed unloaded (km h^{-1}), speed loaded (km h^{-1}) and field measured productivity (m^3 PMH^{-1}) to test the effect of skidder type. Predictive regression models for speed unloaded, speed loaded, field-measured productivity and predicted potential productivity (model predicted productivity given potential payload as above) given the calculated skidder's capacity were developed. Forward stepwise regression was used to isolate key predictive variables. These models were done separately for each variable for both cable and grapple skidders.

As data collection occurred during normal harvesting activities, the harvesting operation as such dictated sample sizes from which the data could be collected. All observations, however, resulted in collected data that exceeded the required amount to describe the respective means with a 95% level of confidence and a margin of error that was within 5% of the true mean.

Results

Table 2 details the number of cycles (*N*) recorded by skidder type, configuration and location. Overall, 207 cycles were measured in the Western Cape, 105 cycles in the Southern Cape and 115 cycles in Eastern Cape/KwaZulu-Natal, i.e. a total of 427 completed extraction cycles.

Data according to skidder type and power output is summarised in Table 3. Other data included are location of individual studies, species extracted, and number of cycles recorded on each site, slope classes and risk factors, harvesting method, and average tree volume extracted from each site. Terrain differed by slope only as soil strength and surface roughness were similar for all sites.

ANOVA results for wander ratio, travel speeds unloaded and loaded

The section below represents the interpretation of ANOVAs for the individual factors: wander ratio, field-measured productivity, and travel speeds both loaded and unloaded. Each interpretation is accompanied by a graphical representation (Figure 1) showing the least square means dependent on the particular main effects. Similar means are marked with the same letter.

Wander ratio

No significant difference was found across the five different skidder types ($p > 0.05$) (Figure 1a). The mean of the wander ratio was 1.12.

Travel speeds unloaded and loaded

Travel unloaded

Significant differences between skidder types were noted for the travel unloaded speed (km h^{-1}) (Figure 1b). The TJ380Cable was significantly different from the other four skidders and the slowest with a mean speed of 4.6 km h^{-1}. No significant difference was observed between the TC625Grapple skidder and the DG640Cable skidder. The fastest skidders were the BL648Grapple and the CR67Cable; while different from the TJ380Cable and the TC625Grapple, no significant difference existed between these two skidders and the DG640Cable.

Travel loaded

Significant differences between skidder types were noted for the travel loaded speed (km h^{-1}) (Figure 1c). With an average travel speed of 8.5 km h^{-1}, the BL648Grapple was the fastest of the five skidder types ($p < 0.05$). The remaining four skidder types were not significantly different from each other and had a pooled mean of 5.5 km h^{-1}.

Field-measured productivity

Significant differences between skidder types were noted for productivity (Figure 1d). The BL648Grapple and the TC625Grapple were not significantly different from each other ($p = 0.20$) but were significantly more productive

Table 3: Summary of relevant compartment data for each of the study locations.

Site	Skidder	Harvest method	Skidder (kW)	Location	Species	Risk factor	Slope class	Average (m³ tree⁻¹)
1	TJ380Cable	Tree-length	113	Western Cape	*P. radiata*	3	4% Gentle	0.34
2	TJ380Cable	Tree-length	113	Western Cape	*P. radiata*	1	0% Level	0.50
3	TJ380Cable	Tree-length	113	Western Cape	*P. radiata*	3	2% Level	0.34
4	TC625Grapple	Full-tree	164	Eastern Cape/ KwaZulu-Natal	*P. elliotii*	3	3% Gentle	1.17
5	TC625Grapple	Full-tree	164	Eastern Cape/ KwaZulu-Natal	*P. patula*	3	4% Gentle	0.64
6	TJ380Cable	Tree-length	113	Western Cape	*P. patula*	1	0% Level	0.25
7	TJ380Cable	Tree-length	113	Western Cape	*P. pinaster*	3	5% Gentle	0.39
8	TC625Grapple	Full-tree	164	Eastern Cape/ KwaZulu-Natal	*P. elliotii*	1	-6% Gentle	1.32
9	CR67Cable	Tree-length	138	Western Cape	*P. radiata*	1	0% Level	0.65
10	TJ380Cable	Tree-length	113	Southern Cape	*P. elliotii*	3	5% Level	0.37
11	BL648Grapple	Full-tree	128	Southern Cape	*P. radiata*	3	5% Level	1.06
12	TJ380Cable	Tree-length	113	Southern Cape	*P. elliotii*	5	10% Moderate	0.54
13	DG640Cable	Tree-length	128	Southern Cape	*P. elliotii*	1	−10% Moderate	1.01

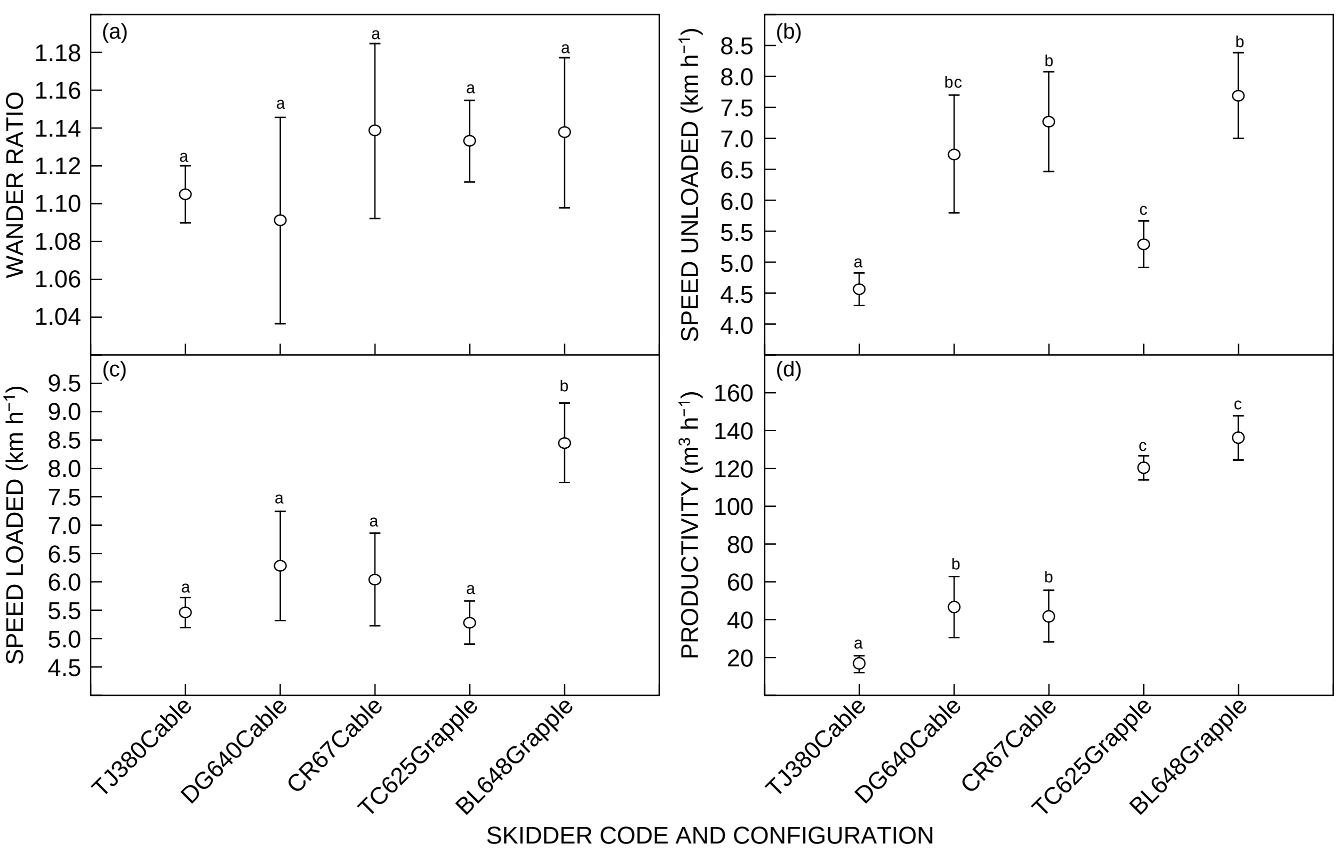

Figure 1: Least square means from ANOVAs for wander ratio (a), speed unloaded (b), speed loaded (c) and in-field productivity (d). Different letters indicate a significant difference in the means ($p < 0.05$). Bars indicate 95% confidence intervals

($p < 0.05$) than cable skidders and had a pooled least square mean of 123.9 m^3 PMH^{-1}. The CR67Cable and the DG640Cable were not significantly different from each other ($p = 1.0$) but were significantly more productive ($p < 0.05$) than the TJ380Cable with a pooled least square mean of 43.9 m^3 PMH^{-1}. The TJ380Cable had the lowest least square mean productivity of 16.4 m^3 h^{-1}.

Tables 4 and 5 show the ANOVA results (wander ratio, travel speeds and productivity) and a summary means for the predictive variables (skidder payload size, extraction distance, slope, loading and unloading times, and potential payload, respectively).

Regression models

Regression models were developed for the variables by skidder configuration (cable and grapple skidders) due to the significant difference across the variables between skidder configurations ($p < 0.05$). Due to no significant difference between skidder types or configurations (Figure 1a, Table 4), a regression model could not be developed for future modelling of wander ratio. The least square mean of 1.12:1 is used. A regression model for potential productivity (across skidder configuration) was also developed, given the potential payload for each skidder type (Table 6).

Travel speed regression models

Speed unloaded regression models

A significant difference between cable and grapple skidders was observed ($p < 0.05$) and therefore separate regression models were developed.

Cable skidder

A forward step-wise multiple regression model was developed for the cable skidders. The input variables were gross power rating (kW), in-field extraction distance (m) and slope (%). The model found gross power rating, in-field extraction distance and slope to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.49 (Table 6).

Grapple skidder

A forward step-wise multiple regression model was developed for the grapple skidders. The input variables were gross power rating (kW), in-field extraction distance (m) and slope (%). The model found gross power rating and in-field extraction distance to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.30 (Table 6).

Speed loaded regression models

Cable skidder

A forward step-wise multiple regression model was developed for the cable skidders. The input variables were gross power rating (kW), payload size (m^3), in-field extraction distance (m) and slope (%). The model found payload size, in-field extraction distance and slope to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.19 (Table 6).

Grapple skidder

A forward step-wise multiple regression model was developed for the grapple skidders. The input variables were gross power rating (kW), payload size (m^3), in-field extraction distance (m) and slope (%). The model found gross power rating, payload size and in-field extraction distance to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.42 (Table 6).

Productivity regression models – field-measured

Field-measured productivity

Cable skidder

A forward step-wise multiple regression model was developed for the cable skidders. The input variables were gross power rating (kW), average tree volume (m^3), payload size (m^3), in-field extraction distance (m), slope (%), loading time (min) and unloading time (min). The model found gross power rating, average tree volume, payload size, in-field extraction distance, loading time and unloading time to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.86 (Table 6).

Table 4: Summary of ANOVA results plus or minus the standard error. Superscript letters indicate similar means corresponding with Figure 1. N = Number of completed extraction cycles

Results	TJ380Cable	CR67Cable	DG640Cable	TC625Grapple	BL648Grapple
N	235	25	18	115	34
Wander ratio			1.12 ± 0.006		
Speed unloaded (km h^{-1})	4.6 ± 0.1^a	7.3 ± 0.4^b	6.7 ± 0.5^{bc}	5.3 ± 0.2^c	7.7 ± 0.4^b
Speed loaded (km h^{-1})		5.5 ± 0.2^a			8.5 ± 0.4^b
Field productivity (m^3 PMH^{-1})	16.4 ± 2.3^a	43.9 ± 7.5^b		123.9 ± 3.9^c	

Table 5: Summary means (± SE) for predictive variables. Different letters indicate a significant difference ($p < 0.05$)

Operation properties	TJ380Cable	CR67Cable	DG640Cable	TC625Grapple	BL648Grapple
Payload (m^3)	2.3 ± 0.1	3.1 ± 0.1	4.8 ± 0.2	5.9 ± 0.2	4.9 ± 0.2
Potential (level ground) payload (m^3)	6.1	5.9	7.8	12.0	9.7
Average extraction distance (m)	93.5 ± 3.8	97.5 ± 3.2	164.9 ± 11.6	98.0 ± 5.1	101.0 ± 11.9
Slope (%)	3.4 ± 0.2	0.0 ± 0.0	−10.0 ± 0.0	−2.1 ± 0.5	5.0 ± 0.0
Loading time (min)		3.65 ± 0.18^a		0.62 ± 0.23^b	
Unloading time (min)	2.1 ± 0.1^a	1.39 ± 0.19^b		0.20 ± 0.10^c	

Grapple skidder

A forward step-wise multiple regression model was developed for the grapple skidders. The input variables were gross power rating (kW), average tree volume (m^3), payload size (m^3), in-field extraction distance (m), slope (%), loading time (min) and unloading time (min). The model found gross power rating (kW), payload size (m^3), in-field extraction distance (m) and loading time (min) to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.54 (Table 6).

Model-predicted potential productivity

Cable skidder

A forward step-wise multiple regression model was developed for the cable skidders. The input variables were gross power rating (kW), average tree volume (m^3), in-field extraction distance (m), loading time (min), unloading time (min) and potential payload (m^3). The model found gross power rating, average tree volume, in-field extraction distance, potential payload and loading time to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.74 (Table 6).

Grapple skidder

A forward step-wise multiple regression model was developed for the grapple skidders. The input variables were gross power rating (kW), average tree volume (m^3), in-field extraction distance (m), loading time (min), unloading time (min) and potential payload (m^3). The model found average tree volume, in-field extraction distance, loading time and potential payload to be significant ($p < 0.05$). The adjusted R^2 for the model was 0.33 (Table 6).

Discussion

Wander ratio

A wander ratio for cable and grapple skidder tree-length and full-tree extraction of 1.12 (±0.006) was found across 427 extraction cycles in 13 harvesting sites and five skidder types (Tables 1–3). Although risk factor varied (Table 2) and was therefore expected to affect wander ratio, this was not found in the context of this study. Nevertheless, wander ratio has important effects on productivity and costs, and operations managers should take it into account when planning the primary transport phase of harvesting. If not considered to provide the true skidding distance and associated time required, planned production can be over-estimated. Given that there was no significant differences across skidder type or configuration (cable versus grapple), a predictive model for wander ratio was not created and the mean of 1.12:1 will instead be used in future modelling.

Travel speeds

Unloaded travel speed

Three skidders (DG640Cable, CR67Cable and BL648Grapple) maintained similar unloaded travel speeds of 7.34 km h^{-1} (Table 4). Two skidders (TJ380Cable and TC625Grapple) were slower, with the TJ380Cable being the slowest of the two at 4.6 ± 0.1 km h^{-1} (Figure 1b). The TC625Grapple's speed was 5.3 ± 0.2 km h^{-1} (Table 4).

Table 6: Summary of linear regression models listing each significant parameter, the respective parameter's coefficient, model *y*-intercept, adjusted R^2 value, and *p*-value. All models are significant

Response variable	Parameter	Gross power rating (kW)	Aerage tree volume (m^3)	Payload size (m^3)	In-field extraction distance (m)	Slope (%)	Load time (min)	Unload time (min)	Potential payload (m^3)	*y*-intercept	Adjusted R^2	*p*-value
Speed unloaded	Cable	0.126			0.023	0.125				−12.290	0.49	<0.001
	Grapple	−0.065			0.016					14.487	0.30	<0.001
Speed loaded	Cable			0.825	0.015	0.096				1.757	0.19	<0.001
	Grapple	−0.081		−0.229	0.011					18.890	0.42	<0.001
Productivity measured	Cable	0.652	10.455	6.031	−0.031		−0.622	−1.389		−66.912	0.86	<0.001
	Grapple	−1.154		22.262	−0.527		−16.919			240.230	0.54	<0.001
Productivity potential	Cable	0.729	24.248		−0.049		−0.549		1.894	−79.160	0.74	<0.001
	Grapple		151.215		−0.443		−26.071		−13.293	163.211	0.33	<0.001

A possible contributor to the TJ380Cable's low unloaded travel speed could be the risk factor of 5 associated with one site (site 12) on which it operated. However, this was one site with only 30 of the 427 cycles measured and should not bias the result to that extent. Although it is likely that sites with higher risk factors will impact travel speed, analysis suggested that it is more likely that poor planning and supervision is the main cause. This statement is supported by the fact that this particular skidder hauled the lowest payload (2.3 m^3), had the longest unloading time (2.1 min) and lowest overall field-measured productivity (16.4 m^3 PMH^{-1}) in the study. When considered in conjunction for sites with higher risk ratings, it becomes likely that the higher risk rating will compound on these planning and supervisory effects.

The slower unloaded (and loaded) travel speeds of the TC625Grapple can potentially be explained by the presence of a bottleneck with the processor positioned at the landing. The skidder operator intentionally slowed down the feeding of the processor in an attempt to alleviate this bottleneck. The main reason for the bottleneck at the processor was the greater payload delivery of the TC625Grapple over a relatively short average extraction distance of 98.0 ± 5.1 m. The TC625Grapple was not being utilised to its full potential extent, which was the reason for its slower speeds both loaded and unloaded.

From the results and the discussion above, an unloaded travel speed of 7.3 ± 0.5 km h^{-1} (calculated as the weighted mean of similar skidders by cycle count, excluding the TJ380Cable due to perceived operational problems and the TC625Grapple due to the processor bottleneck) can be accepted as an achievable and sustainable speed for the unloaded travel phase of primary transport under the conditions observed.

For comparison purposes, similar work by Mousavi (2012a) found average travel speeds of a Timberjack 450C cable skidder unloaded to be 5.9 km h^{-1}. This finding is lower than that found in the present study, which can be attributed to the steep terrain in which the Mousavi (2012a) study was conducted quite likely requiring slower average travel speeds. Curro and Verani (1990) and Colton and Brink (1999) found travel unloaded speeds to range between 3.7 and 10.1 km h^{-1}. The present study's results are in the upper range of what both studies suggested, potentially attributed to advances in skidder technology over the past decade.

Loaded travel speed

For loaded travel speeds, the results were much clearer. The BL648Grapple had a significantly different loaded travel speed (8.5 ± 0.4 km h^{-1}) (Figure 1c) from that of the other four skidders, which maintained a loaded speed of 5.5 ± 0.2 km h^{-1} (Table 4). The BL648Grapple, which was also the fastest in the unloaded travel segment, was in the opinion of the data collectors being operated at potentially unsustainable speeds (e.g. harsh braking, careless turning and driving over stumps and decked timber) and should possibly be excluded as a contributor to the study as far as loaded travel speeds are concerned. The fact that the BL648Grapple was timed on a wage payment day most likely also contributed to the operator's possibly reckless driving performance, with the intension of completing his target volume as early as possible to get home.

Once again the TJ380Cable is the slowest of the five skidders, yet due to the wide range of travel speeds of the other skidders, it is not significantly different from the DG640Cable, CR67Cable and TC625Grapple. Curro and Verani (1990) and Colton and Brink (1999) found loaded travel speeds between 2.4 and 5.0 km h^{-1}. Odhiambo (2010) and Mousavi (2012a) found loaded travel speeds of 5.9 km h^{-1} and in a follow-up study (Mousavi 2012b) speeds between 6.2 and 7.7 km h^{-1}. The present study's finding for loaded speeds essentially lie in the middle of the wide-ranging speeds gleaned from the literature and therefore seem credible in the context of the study.

Productivity (field-measured and model-predicted potential productivity)

Overall achieved skidder payloads were found to be approximately 50% (Table 5) of potential skidder payloads as calculated using the FAO (1977) method (Table 5). While it can be argued that potential maximum payloads are not always possible due to piece diameters and lengths, choker capacity on the mainline and butt plate area on cable skidders to receive tree-lengths, grapple dimension, tree presentation, adequate bunching by feller-bunchers, chokersetter ability and general harvest planning, it does provide a benchmark for discussion on improving the efficiency of skidding operations and, more importantly, machine utilisation. A skidder's average extraction distances should be limited to about 125 to 150 m (MacDonald 1999). Hauling low payloads with long terminal times over these and longer distances impacts machine utilisation, costs and seriously reduces productivity, as found in this study where field-measured productivity was found to be low (Tables 4 and 5).

Field-measured productivity was significantly different between cable (43.9 ± 7.5 m^3 PMH^{-1}) and grapple skidders (123.9 ± 3.9 m^3 PMH^{-1}) if the TJ380Cable (16.4 ± 2.3 m^3 PMH^{-1}) is excluded for reasons mentioned above. There are several other factors explaining the comparatively low performance of the TJ380Cable, such as the low average payload of 2.3 m^3, as opposed to a potential payload of 6.1 m^3. Terminal times (loading averaging 3.8 min and unloading averaging 2.1 min) were significantly longer than for the other skidders. The TJ380Cable travelled significantly slower in the unloaded direction (4.6 km h^{-1}) (Tables 3 and 4).

A full payload for the TJ380Cable of 0.375 m^3 trees would consist of between 15 and 17 tree-lengths as opposed to the average of 6.3 tree-lengths recorded during the study (Tables 2 and 4). A main line system with a single set of a limited number of chokers was used and the time taken to load and unload was longer than the average of the other cable skidders (Table 5). Tagline choking systems have proven to be beneficial over main-line choking systems when extracting small-dimension timber (Odhiambo 2010), as they potentially increase payloads and reduced terminal times. In any case, it would have been better to have more chokers and skid bigger payloads despite the associated increase in loading and unloading times. The points mentioned all point to operational inefficiencies related to less than optimal harvest planning and supervision.

The higher productivity of grapple skidders is well known but confirmed by Kluender et al. (1997). The under-utilisation of the TC625Grapple, which is most likely to continue with typical short average extraction distances, meant that the productivity of the two grapple skidders was not significantly different. The TC625Grapple maintained a reasonably high payload of 5.9 m^3 and short loading time of 0.6 min as opposed to the BL648grapple's payload of 4.9 m^3 and loading time of 0.8 min (although the loading time was not statistically different). Mean operating slopes for the TC625Grapple and the BL648Grapple were −2.1% and 5.0% (Table 2), respectively, meaning that the former operated on a more favourable slope.

In terms of terminal times (loading and unloading) there were significant differences between cable (3.65 ± 0.18 min and 1.39 ± 0.19 min) and grapple skidders (0.62 ± 0.23 min and 0.20 ± 0.10 min) apart from the TJ380Cable, which had a slower and significantly different unloading time (2.1 ± 0.1 min).

Regression models

Empirical models can be useful for describing the relationship between machine performance and different stand and operational parameters. For this reason models were built for predicting travel speeds (both loaded and unloaded) and productivity (both field measured and predicted potential) for cable and grapple skidders separately.

In all cases (Table 6) in-field extraction distance (including the wander ratio), was included in the models, which is consistent with the findings of Egan and Baumgras (2003), Wang et al. (2004), Hogg et al. (2010) and Mousavi (2012a, 2012b). Slope was included only for the speeds loaded and unloaded for the cable skidders. Gross power rating (kW) was not included in the regression models for speed loaded of the cable skidders and payload size (current and potential) was included in all models except for speeds unloaded and in cable skidder productivity modelling. Loading times were included in all productivity regressions (both field measured and predicted potential), but unloading only in the case of cables skidders at field measured payload sizes. Adjusted R^2 values were the highest for the cable skidders' productivity regressions ranging from 0.86 for field-measured productivity and 0.74 for model-predicted potential productivity. Speed loaded for the cable skidders was the most difficult to predict (adjusted R^2 of 0.19). This is most likely a result of the factors mentioned above causing more variation in the cable skidder operations than in those of the grapple skidder. All regression models were significant ($p < 0.05$).

Information regarding wander ratio, travel speeds and productivity (field measured and predicted potential) predictors for both machine types over the sites studied will provide input into the network analysis of the softwood sawtimber supply chain.

Conclusion

Developing predictive models for wander ratio, skidder speeds (both unloaded and loaded) and productivity (both field measured and potential) in a South African context was the main objective of this study. Five skidder types (both cable and grapple) over 13 individual sites in the Western, Southern and Eastern Cape and KwaZulu-Natal were studied. Four-hundred and twenty-seven extraction cycles were recorded utilising OBC systems supported by time study over varying terrain in terms of tree sizes and species. Skidders of different makes, configurations and power ratings were studied. In addition, predictive models were developed for cable and grapple skidder loaded and unloaded travel speeds and productivity (both field measured and predicted). The wander ratio was also determined for the skidding operations.

The study found that both cable and grapple skidders were hauling approximately 50% of their payload capacity. For this reason predicted potential productivity multiple regression models at full potential payload were developed for the two skidder types. Due to insignificance across skidder types and configurations, the objective of creating a predictive model for skidder wander ratio was not met. The overall mean wander ratio was 1.12:1. No difference was found for unloaded and loaded travel speeds between skidder type and speeds were found to be 7.3 km h^{-1} and 5.5 km h^{-1}, respectively. In terms of productivity, when based on field-measured data there were differences between skidder types with cable skidders achieving 43.9 m^3 PMH^{-1} and grapple skidders 123.9 m^3 PMH^{-1}. Multiple regression was used to develop prediction models for travel speeds loaded and unloaded.

The study met its objectives as far as model development for travel speeds loaded and unloaded and productivity. However, due to insignificance across skidder types and configurations, a predictive model for skidder wander ratio was not met and an overall mean of all skidders is used. This figure and other models will be included in a subsequent network analysis to provide solutions to optimising the softwood sawtimber supply chain. The study also found that the human element has an impact on the factors studied, and that good training, planning, implementation and operational control are imperative to ensure supply (or value) chain goals are met.

Acknowledgements — The authors would like to acknowledge the South African forestry sawtimber industry for making their operations available for field work related to this study. The authors acknowledge the input of a number of UBC exchange students who assisted with data collection.

References

Bredenkamp BV. 2000. Plantation inventory. In: Owen DL (ed.), *South African forestry handbook*, vol. 1 (4th edn). Pretoria: South African Institute of Forestry. pp 161–174.

Cavalli R, Grigolato S, Lubello D. 2006. Planning logging systems through site analysis. In: Ackerman PA, Längin DW, Antonides MC (eds), *Precision forestry in plantations, semi-natural and natural forests: proceedings of the International Precision Forestry Symposium, 5–10 March 2006, Stellenbosch, South Africa*. Stellenbosch: Department of Forestry and Wood Science, Stellenbosch University. pp 319–330.

Colton ALC, Brink MP. 1999. Hitching optimal payloads increases skidder productivity. *Southern African Forestry Journal* 186: 29–32.

Cordero R, Mardones O, Marticorena M. 2006. Evaluation of forestry machinery performance in harvesting operations using GPS technology. In: Ackerman PA, Längin DW, Antonides MC (eds), *Precision forestry in plantations, semi-natural and natural forests: proceedings of the International Precision Forestry Symposium, 5–10 March 2006, Stellenbosch, South Africa*. Stellenbosch: Department of Forestry and Wood Science, Stellenbosch University. pp 163–173.

Curro P, Verani S. 1990. On the maximum skidding output of the "Timberjack 380" forest tractor. *Journal of Forest Engineering* 1(2): 35–39.

Davis CJ, Reisinger TW. 1990. Evaluating terrain for harvesting equipment selection. *Journal of Forest Engineering* 2(1): 9–16.

Egan AF, Baumgras JE. 2003. Ground skidding and harvested stand attributes in Appalachian hardwood stands in West Virginia. *Forest Products Journal* 53(9): 59–63.

Erasmus D. 1994. *National terrain classification for forestry.* Compiled on behalf of the National Terrain Classification Co-operative. *ICFR Bulletin Series* 11/94. Pietermaritzburg: Institute for Commercial Forestry Research.

FAO (Food and Agriculture Organization of the United Nations). 1977. *Planning forest roads and harvesting systems*. Forestry Paper no. 2. Rome: FAO.

Folegatti B. 2010. The application of precision forestry technologies in logging operations. MSc thesis, Auburn University, Alabama, USA.

FSA (Forestry South Africa). 2011. Abstract of South African forestry facts for the year 2010/2011. Rivonia: Forestry South Africa.

Hogg GA, Pulkki RE, Ackerman PA. 2010. Multi-stem mechanized harvesting operation analysis – application of Arena 9 discrete-event simulation software in Zululand, South Africa. *International Journal of Forest Engineering* 21(2): 14–22.

Kluender R, Lortz D, McCoy W, Stokes B, Klepac J. 1997. Productivity of rubber-tired skidders in southern pine forests. *Forest Products Journal* 47(11/12): 53–58.

Kopka A, Reinhardt B. 2006. Accuracy of GPS/GIS applied harvester skidding tracks. In: Ackerman PA, Längin DW, Antonides MC (eds), *Precision forestry in plantations, semi-natural and natural forests: proceedings of the International Precision Forestry Symposium, 5–10 March 2006, Stellenbosch, South Africa*. Stellenbosch: Department of Forestry and Wood Science, Stellenbosch University. pp 149–162.

MacDonald A J. 1999. *Harvesting systems and equipment in British Columbia*. FERIC Handbook no. HB-12. Vancouver: Forest Engineering Research Institute of Canada.

Marklund B. 1987. Torque distribution on wheeled vehicles affects damage on the forest ground. In: Proceedings of the 9th ISTVS Conference, 31 August–4 September 1987, Barcelona, Spain, vol. 1. Hanover, New Hampshire: International Society for Terrain-Vehicle Systems. pp 347–354.

Mousavi R. 2012a. Time consumption, productivity, and cost analysis of skidding in the Hyrcanian forest in Iran. *Journal of Forestry Research* 23: 691–697.

Mousavi R. 2012b. Effect of log length on productivity and cost of Timberjack 450C skidder in the Hyrcanian forest in Iran. *Journal of Forest Science* 58: 473–482.

Odhiambo BO. 2010. The use of time study, method study and GPS tracking in improving operational harvest planning in terms of system productivity and costs. MSc thesis, Stellenbosch University, South Africa.

Pellegrini M, Ackerman P, Cavalli R. 2013. On-board computing in forest machinery as a tool to improve skidding operations in South African softwood sawtimber operations. *Southern Forests* 75: 89–96.

Saarilahti M. 2002. Soil Interaction Model. Development of a protocol for ecoefficient wood harvesting on sensitive sites (Ecowood). Quality of Life and Management of Living Resources Contract no. QLK5-1999-00991. Department of Forest Resource Management, University of Helsinki.

Spong BD. 2001. A mobility, production, and rut depth simulation program. Master of Forestry thesis, Oregon State University, USA.

Suvinen A. 2006 A GIS-based simulation model for terrain tractability. *Journal of Terramechanics* 43: 427–449.

Suvinen A, Saarilahti M, Tokola T. 2003. Terrain mobility model and determination of optimal off-road route. In: Virrantaus K, Tveite H (eds), *ScanGIS'2003: proceedings of the 9th Scandinavian Research Conference on Geographical Information Science, 4–6 June 2003, Espoo, Finland*. Espoo: Helsinki University of Technology. pp 251–259.

Terlesk CJ. 1983. A proposed terrain classification for harvesting in New Zealand. *New Zealand Journal of Forestry* 28: 43–57.

Tiernan D, Zeleke G, Owende PMO, Kanali CL, Lyons J, Ward SM. 2004. Effect of working conditions on forwarder productivity in cut-to-length timber harvesting on sensitive forest sites in Ireland. *Biosystems Engineering* 87: 167–177.

Wang J, Long C, McNeel J, Baumgras J. 2004. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. *Forest Products Journal* 54(12): 45–51.

Warkotsch WP. 1988. Harvesting of pine and eucalypt in South Africa. *South African Forestry Journal* 147: 37–52.

Received 11 August 2013, revised 8 January 2014, accepted 2 February 2014

Southern Forests 2014: xx–xx
Printed in South Africa — All rights reserved
This is the final version of the article that is
published ahead of the print and online issue

SOUTHERN FORESTS
ISSN 2070-2620 EISSN 2070-2639
http://dx.doi.org/10.2989/20702620.2014.984150

Chapter 5: Softwood sawlog secondary transport travel speed prediction for theSouth African forestry industry

Pierre A Ackerman[1*], Reino E Pulkki[1,2] and Elizabeth Gleasure[1]

[1] *Department of Forest and Wood Science, University of Stellenbosch, Stellenbosch, South Africa.*
[2] *Faculty of Natural Resources Management, Lakehead University, Thunder Bay, Ontario, Canada*
** Corresponding author, e-mail: packer@sun.ac.za*

The objective of this study was to develop a predictive model for travel speed of softwood sawlog timber transport (STT) vehicles over a range of forest and provincial roads of varying condition for the South African forestry industry. Data was accumulated from both the Eastern Cape/KwaZulu-Natal and Mpumalanga forest regions of South Africa. Vehicle location and payload data were collected remotely using a combination of GPS tracking and remotely sensed data. Road condition, including road width, was assessed for each identified road segment in-field according to a visual condition indicator (VCI) index. Two STT contractors were selected from each forest region transporting pine sawlogs directly from compartment roadside landings to either a processing plant or log storage area. Five STT vehicle types, representative of transport operations in the two forest regions, were assessed. Principal component analysis was conducted to determine the degree of communality between the respective predictor variables combining road width and VCI as one factor, and truck maximum power and the percentage of (legal) maximum payload as a second factor. Comparisons of the correlations between average speed and the respective predictor variables showed that road width and percentage of maximum (legal) payload had the highest correlations. Multiple linear regression of these two factor variables were used in the model showing both variables as significant (p □ 0.05) with an adjusted r^2 value of 0.52.

Keywords: payload, road width, satellite truck tracking, sawlogs, secondary transport, truck travel speeds, visual road condition indicator

---

Introduction

In 2011, 18.5 million m^3 of roundwood was produced from South African industrial plantations (FSA 2011). Of this, 4.5 million m^3 was softwood sawlogs (FSA 2011). Unlike the transport of roundwood or chipped pulpwood, the majority of softwood sawlogs are transported directly from roadside landings to processing plants located throughout the country for conversion to board products. The presence of a good road network is a prerequisite for sustainable wood procurement; and the major design criterion of forest roads is to maintain and sustain high vehicle travel speeds (Uusitalo 2010). Seeing that most forest roads are unpaved, road attributes such as road width, line of sight, road gradient and road surface condition, amongst other factors, play a role in the efficiency of secondary roundwood transport.

Roads are generally constructed to specified standards depending on individual road service requirements, which are, amongst others, the road's ability to carry planned axle loadings, allowing vehicles to maintain a desired travel speed and carry expected traffic volumes, availability of the road in varying weather conditions, and the expected useful life of the road (Kennedy 1986). Roads are therefore built to certain standards, but not all roads are required to provide the same service throughout their useful life. On the other hand, road condition, a function of road maintenance, affects vehicle travel speeds; the poorer the road's surface condition, the slower the likely travel speed and the higher the cost of transport, and therefore the greater the potential of wood delivery interruptions.

The objective of this study was to develop a predictive travel speed model for sawlog timber transport (STT) vehicles over forest and provincial roads in both the loaded and unloaded directions in the South African forest industry.

Background

Effect of road design

The effect of road design, particularly road geometry and road condition, on STT haulage costs have been examined in detail by Byrne et al. (1960), Jackson (1986) and Groves et al. (1987). Byrne et al. (1960) identified influences of STT vehicle travel time to be road gradient, nature of the road surface, sight distance, psychological factors and the ratio of effective horsepower to gross vehicle weight. In the study by Byrne et al. (1960), road surfaces were classified as paved (asphalt or concrete) or compacted gravel, with road roughness influenced by both the type of surface material and the compactness thereof. Byrne et al. (1960) also used field observations and power equations to develop an empirical model for STT vehicle speed as a function of gradient over both adverse (uphill) and favour-able (downhill) road grades.

Jackson (1986) investigated several independent variables influencing STT vehicle travel speeds over forest roads, such as grade, curve radius, road width, ditch depth, super-elevation, sight distance, time of day and net engine horsepower. It was found that grade, when steeper than 11%, and curve radius were the most important factors affecting STT vehicle travel speeds in western Oregon.

Groves et al. (1987) developed a road condition classification system based on road function and condition and used this classification to predict STT vehicle travel times along timber haulage routes in north-west Tasmania. The road condition classes broadly assessed surface roughness (good, moderate or rough), grade and alignment. Furthermore, Groves et al. (1987) found that travel times were proportional to distance and factors such as road condition, driver and truck had a multiplicative rather than additive effect on travel time.

The use of GPS and other remote-sensing tracking technologies has made tracking vehicles more efficient for both cost of data acquisition and time. Furthermore, additional parameters such as fuel consumption, harsh braking and engine idling time can also be recorded (Devlin et al. 2009) together with positional data. Prisley and Carruth (1995) used GIS/GPS for route optimisation, balancing the production effort in timber harvesting and creating a complete road network database for South Carolina. Average travel speeds were determined for all road segments travelled using ArcGIS. Having created a consistent and comprehensive classification system for the entire road network, average travel speeds could then be used to determine average road speeds for each road including roads that were not travelled during the data collection period (Prisley and Carruth 1995).

More recent studies have focused on other aspects of STT vehicle tracking, including verification of optimal haulage routing algorithms (Devlin et al. 2008), comparisons of different GPS devices (Devlin et al. 2009) and development of simulation models that can be used to accurately predict travel time of vehicles (Simwanda 2010).

Visual road assessments of road surface conditions

Unsealed roads are roads where vehicles travel directly on natural material since the road has no formal surfacing (e.g. bitumen, concrete or block paving) (Jones and Paige-Green 2000) and most, if not all, forest roads fall into this category. Unsealed roads are dynamic systems and require different condition assessment and management methods than sealed road surfaces. Forest road surface condition assessments can be completed using visual assessments, quantitative measurements, radar systems or a combination of these methods. Visual assessments are cost-effective and aid in determining road condition indices that are useful for making road management decisions (Jones and Paige-Green 2000).

Several protocols for visual assessment of gravel road conditions are used globally (Chong and Wrong 1989; US Department of the Army 1995; Jones and Paige-Green 2000; Saskatchewan Highways and Transportation 2001; Walker 2002; van der Gryp and van Zyl 2007). In South Africa, Jones and Paige-Green (2000) developed *Draft TMH12: Pavement Management Systems: a Standard Visual Assessment Manual for Unsealed Roads*. This protocol assesses the type, degree and extent of road surface defects affecting the road surface condition and the information is used to calculate a visual condition index (VCI). The appearance of road surface defects are varied and often complex to evaluate in combination. The task of describing a road surface defect is achieved by recording its main characteristics – so-called attributes of distress. The attributes referred to in this manual are type, degree and extent (Jones and Paige-Green 2000). Van der Gryp and van Zyl (2007) went a step further by adapting Jones and Paige-Green's TMH12 for assessing gravel roads into the Gravel Road Management System for South Africa.

The US Army Corps of Engineer's technical manual on unsurfaced road maintenance management (US Department of the Army 1995) describes a road condition assessment protocol that includes both visual assessment and detailed measurement components. Measurements include the severity of seven predetermined road surface defect factors, such as inadequate cross drainage and roadside drainage, presence of corrugations, potholes, ruts and loose aggregates, and occurrence of dust. From these an unsurfaced road condition index on a scale of 0–100 is calculated and these ratings can aid in the decision-making process for management activities (US Department of the Army 1995). Other North American road surface evaluation protocols are loosely based on this manual (Chong and Wrong 1989; Saskatchewan Highways and Transportation 2001; Falls et al. 2003).

Plantation forest roads in South Africa are classified based on their suitability for vehicle travel and geometric characteristics. These parameters are formalised through the creation of descriptive road classes (Department of Environmental Affairs 1982).

However, the impact of road width, road surface conditions, gradient, different vehicle configuration and vehicle payload on vehicle speeds are not clear from any of the studies reviewed above. In addition, no literature concerning softwood transport in the South African forest industry could be found.

Methodology

Study locations and STT vehicles

Eastern Cape/KwaZulu-Natal and Mpumalanga STT operations were selected as the study sites. These forest regions were used because they represent 64% of the total land area of sawlog-producing plantations in South Africa and the three regions produce 68% of the total sawlog production of South Africa (FSA 2011). A further consideration was the ease of data collection. As data were to be remotely acquired, STT vehicles would of necessity have to be equipped with satellite tracking devices and linked to remote vehicle management services. This was the case in the regions selected as opposed to the other forestry regions in South Africa. The Eastern Cape and KwaZulu-Natal were grouped together as sawlogs are transported across provincial boundaries from Eastern Cape plantations to a mill located in KwaZulu-Natal and vice versa. Two STT contractors were selected from each of the two regions. STT was studied over 18 plantations: three in the Eastern Cape/KwaZulu-Natal and the balance in Mpumalanga. The study represented five STT vehicle types, each with specific engine kilowatt ratings (Table 1), representative of the four transport contractors' typical operations. Individual STT vehicles and their drivers were selected through a remote random selection process and drivers remained the same during data collection. Ten individual STT vehicles (five in Eastern Cape/KwaZulu-Natal and five in Mpumalanga) were monitored over three separate periods between 2011 and 2013. The drivers were considered trained and familiar with their vehicles and tasks for the purposes of this study. It was assumed that the STT vehicles were roadworthy and suitable to the task of sawlog transport. It was not possible to replicate each vehicle type in each of the regions studied due to the widely spread geographic locations between Eastern Cape/KwaZulu-Natal and Mpumalanga. All data was accumulated remotely, so any human-induced effects on truck operation and hence achieved travel speeds could not be evaluated.

Data collection

Data were collected from STT vehicles during normal secondary transport operations over a range of forest roads of differing road condition from roadside landings to either processing plants or log storage sites. As the data were collected remotely, the study represented typical year-round operations. Vehicle, road location and payload data were collected using a combination of GPS tracking and remotely sensed data collection as detailed below.

GPS tracking was done using the online capabilities of Fleet Manager Professional (FM Pro) version 9, provided by MiX Telematics, Johannesburg, South Africa. The product website, along with support software, linked transportation contractors with their vehicles equipped with GPS and provided downloadable and real-time data on various attributes of the vehicle, such as location and speed. The website overlaid the GPS tracks of a particular STT vehicle for a specified time period over a current map of the region it was active in. Using the overlay and local knowledge of plantations in the area, it was determined where the STT vehicle had been recently operating on unsurfaced forest and provincial roads. The same field crew evaluated the surface conditions of each road travelled in each region for the duration of the study. At each data point the GPS recorded date, time, latitude, longitude, altitude, heading, number of satellites, the horizontal dilution of precision and speed.

Vehicle payload

Vehicle (design gross loaded and unloaded masses and tare masses) (Table 1) were provided by vehicle manufacturer's specifications. Permissible (legal) gross masses were calculated based on Regulation 241 (RSA 1996). STT vehicle payloads were obtained from real-time vehicle tracking information via mounted weigh-scales. Maximum potential legal payloads were determined from the difference between permissible gross mass (Regulation 241; RSA 1996) and the vehicle unladen (tare) masses. Minimum, average and maximum payloads were compared to this value (Table 1). To address the possibility of STT vehicles being either under- or overloaded, and to ascertain this effect on potential travel speeds, a method was developed whereby a percentage of the actual measured payload to the legal payload was calculated for inclusion in the eventual predictive model (Equation 1). The percentage of legal load was calculated as follows:

$$\text{Maximum load (\%)} = \frac{\text{Payload load mass}}{\text{Legal gross mass} - \text{tare weight}} \times 100 \quad (1)$$

Unloaded trucks therefore had a load percentage of 0.0%, as they carried only their tare weight and trucks loaded to their respective maximum legal masses had a load percentage of 100%. Overloaded trucks had load percentages exceeding 100% and vice versa for underloaded trucks.

Table 1: Vehicle technical specifications

Specification	Mercedes-Benz Axor 3340/45 (6×4) F/C (Eastern Cape/ KwaZulu-Natal)	Nissan UD350 (6×4) F/C (Eastern Cape/ KwaZulu-Natal)	MAN TGA 33.400 (6×4) BBL (Mpumalanga)	MAN TGA 33.480 (6×4) BB (Mpumalanga)	Volvo FH 13.400 (6×4) LTR (Mpumalanga)
Contractor	A	B	C	D	C
Truck configuration	Rigid 6 x 4	Rigid 6 x 4	Rigid 6 x 4	Rigid 6 x 4	Rigid 6 x 4
Truck manufacturer's gross vehicle mass (kg)	26 000	26 000	33 000	33 000	29 000
Truck tare mass (kg)	10 240	11 680	9 340	9 469	9 171
Truck maximum torque	2 000 Nm @ 1 100 r min^{-1}	1 470 Nm @ 1 100 r min^{-1}	1 900 Nm @ 1 000 r min^{-1}	2 300 Nm @ 1 050 r min^{-1}	2 000 Nm @ 1 050 r min^{-1}
Engine displacement (l)	12.0	13.1	10.5	12.4	12.8
Truck maximum power (kW @ r min^{-1})	295 @1 900[a]	257 @ 1 800[b]	294 @ 1 800[c]	353 @1 900[d]	294 @ 1 800[c]
Trailer configuration	3-axle semi-trailer	2-axle semi- trailer	4-axle drawbar trailer	4-axle drawbar trailer	4-axle drawbar trailer
Trailer tare mass (kg)	5 680	4 200	6 350	6 500	6 500
Trailer gross vehicle mass (kg)	16 400	16 400	32 050	32 050	32 050
Truck and trailer tare mass (kg)	15 920	15 800	15 690	15 969	15 671
Permissible gross vehicle combination (truck and trailer) mass (kg) (Regulation 241)	48 000	40 000	56 000	56 000	56 000
Maximum legal payload (kg)	32 080	24 200	40 310	40 031	40 329

Road assessment

For road condition assessment, roads traversed by the STT vehicles were divided into road segments. Road segments were identified as a section of road that differed in respect of surface condition, change in gradient greater than 5% (either positive or negative), and road width, and were defined during the road surface assessment process by the two surface condition assessors as mentioned above.

The average widths of each road segment were measured during the road condition assessment. Road width is defined as the width of running surface and road shoulder. Provincial roads were not assessed for either condition or width and were assumed to have a road width of 15 m (SANRAL 2003, 2012). A wide representation of road widths was observed and recorded across all forest roads.

Road surface condition

Two trained road assessors, for purposes of objectivity, followed the STT vehicle routes and recorded data necessary for road surface condition assessment on all roads traversed for the entire study. A methodology proposed by TMH12 (Jones and Paige-Green 2000) for the visual classification of road surface conditions was used for the assessment. The full TMH12 list of defects considers many road condition factors beyond those that immediately impact STT vehicle travel speeds. As a result, only certain defects were selected due to their potential impact on travel speeds to make the assessment procedure more time efficient. Road surface defects assessed were: potholes, rutting, corrugations, loose material, embedded stones, loose stones, dustiness and operator driving comfort riding quality. Each road surface defect was given a degree and extent rating, on a scale of 1 (very good) to 5 (very poor), with the exception of dustiness, which was only given a degree rating in accordance with the TMH 12 methodology (Jones and Paige-Green 2000). Degree ratings corresponded to the severity of the observed defect and extent covered the area of the road segment over which the defect was observed.

Results from the visual assessment were used as input for the VCI equations (Equations 2–5) as it appears in the TRH22 (Department of Transport 1994). Although this formula was originally developed for paved road systems, the formula was adapted for use on unpaved roads through weighting the selected defects equally as none could be shown to inhibit speed more than the other defects. From the visual assessment, a preliminary road surface condition index (VCI_p) was calculated, which was then converted into a percentage-scale VCI value. VCI values fell onto a scale ranging from 0 (very poor) to 100 (very good) (Table 2). The calculated VCI values were compared to the qualitative ranking by the road assessors and, because the qualitative ranking matched the observed road conditions, the VCI formula was considered suitable for this study. A and B refer to coefficients developed from the TRH 22 methodology (Department of Transport 1994).

$$F_n = D_n * E_n * W_n \tag{2}$$

$$C = \left[\sum_{n=1}^{N} F_n(\max) \right]^{-1} \tag{3}$$

$$VCI_p = \left[1 - C * \left\{ \sum_{n=1}^{N} F_n \right\} \right] \tag{4}$$

$$VCI = (a * VCI_p + b * VCI_p^2)^2 \tag{5}$$

where VCI_p = preliminary road surface condition, $F_n(\max)$ = 25 (the maximum road surface defect and extent possible), W_n = weight of defect (considered to be equal among the criteria and therefore equal to 1), a = 0.02509, b = 0.0007, D_n = degree rating of each road surface defect (scale of 1–5), and E_n = extent rating of each road surface defect (scale of 1–5).

Tarred provincial roads were not formally assessed and were assumed to be in good condition (as opposed to very good) and given a constant VCI of 80. A STT vehicle may travel repeatedly on a segment with each trip across a road segment recorded, and these trips provided the input data for this study.

Statistical analysis

Statistical analysis was done using Statistica version 12 (StatSoft, Tulsa, OK, USA, 2014). A principal component analysis was used to isolate the collinear factors followed by a multiple regression analysis for model development.

Results

Vehicles were tracked over an excess of 43 000 km. The majority of the data were collected from the Mpumalanga region (40 684 km) with the Eastern Cape/KwaZulu/Natal contribution 2 400 km to the data set. Road widths ranged from 3 to 8 m on unpaved forest roads and were assumed to be 15 m on paved provincial roads (SANRAL 2003, 2012). Multiple trips were made over individual segments and a total of 96 unique segments were evaluated. VCI values ranged from 15 (very poor) to 76 (good) on unpaved roads.

Analysis of the load data found that overloading was a common occurrence, particularly in Eastern Cape/KwaZulu-Natal (Table 3). Truck payloads ranged from a minimum of 29% to a maximum of 175% of the maximum legal required load.

Principal component analysis was conducted to determine the degree of communality between the respective predictor variables. Analysis of the eigenvalues determined that two factors explained 57% of the total variation. The principal components of the factor loadings combined Road Width and VCI as factor one (referred to as the Road Condition Factor) and Truck Maximum Power and Percentage of Maximum Load were grouped into a second

Table 2: Visual condition indicator (VCI) value and respective qualitative ranking

Qualitative ranking	VCI value
Very poor	$0 < VCI \leq 35$
Poor	$35 < VCI < 50$
Fair	$50 < VCI < 70$
Good	$70 < VCI < 85$
Very good	$85 < VCI \leq 100$

factor (referred to as the Truck Performance Factor). Average Gradient was not grouped.

Correlations were then compared between average speed and the respective predictor variables and showed that Road Width had a higher correlation (0.69) than VCI (0.50) with average speed. The Percentage of Maximum Load also had a higher correlation (−0.16) than Truck Maximum Power (0.09). Average Gradient was not significantly correlated with Average Speed (0.02) and hence excluded.

This procedure was also repeated for the individual regions. For the Road Condition Factor, Road Width was more highly correlated than VCI for both regions individually and combined. Under the Truck Performance Factor, Percentage of Maximum Load was more highly correlated than Truck Maximum Power for both regions and combined.

Given the results of the factor analysis and the correlations, the entire data set was used to construct a predictive model for STT travel speeds. Multiple linear regression of the two highest correlated factor variables (Road Width and Percentage of Maximum Load) were used in the model. Both variables were significant ($p < 0.05$). The adjusted r^2 value for the model was 0.52. The model explained just over half of the variation within the data (Equation 6).

$$\text{Average speed} = -5.9 \text{ Percentage max load} + 2.5 \text{ Road Width} + 8.1 \quad (6)$$

Discussion

The study produced a predictive travel speed model for softwood STT from travel speed data accumulated in Eastern Cape/KwaZulu-Natal and Mpumalanga sawlog-producing forest regions of South Africa. Of all the variables considered for the model, i.e. road width, gradient, road surface condition, vehicle maximum engine power and payload, the analysis showed that payload (expressed as a percentage of a maximum legal load) and road width were significant predictors of travel speeds.

Average gradient was not a significant predictor variable for travel speed. Forest roads in South Africa have historically been well designed in terms of both vertical and horizontal alignment and are as such largely independent of terrain. This means roads are essentially rather gentle in gradient as reflected in the fact that the average gradient, both favourable and adverse, was 2% in Eastern Cape and 0% in Mpumalanga. The global average was 0.4% favourable and 0.6% adverse.

Although road class was recorded during initial data collection to ensure representation of all possible variables of forest roads for each road segment in the study, it was discarded as a preferred indicator variable in favour of road width. The reasoning for this was that road width provides a numerically continuous description of the relationship between the different road classes found on plantation roads; it has a clear definition and is more easily measured. In addition, road width is an objective rather than a more subjective (as in the case of road class) variable. In the case of a choice between sight distance and road width as predictor variables, and although sight distance does have an impact on travel speed, increasing road width implies increased sight distance (narrow vs wider road) and hence increased speed (Byrne et al. 1960; Morkel 1994). Byrne et al. (1960) mentions that anything that increases sight distance (i.e. road width) will increase travel speed. In addition, Jackson and Sessions (1987) found that sight distance was not an important variable in predicting speed. Byrne et al. (1960) and Morkel (1994) found that a reduction in lane width can cause a reduction in travel speed of up to 1 km h^{-1} per 0.3 m reduction in road width. Finally, because road width is also more easily and objectively measured than sight distance, it was selected as the key predictor variable rather than the categorical road class or collinear sight distance.

The model was unsurprising concerning payload, as intuitively an increase in vehicle load should decrease travel speed and vice versa. The extent of overloading was somewhat unexpected and, because of its prevalence, a somewhat unique approach to account for it in the predictive model generation was necessary. The use of a percentage value (0% representing unloaded vehicles, and above or below 100% representing loaded vehicles with 100% as the ideal load), worked well in the prediction model by allowing for consideration of differing payload sizes as well as the direction of truck travel. It was hence possible to generate only one equation providing a predictive model for travel speed. No reference to this method could be found in the literature.

Overloading is generally problematic in South Africa and not only in STT transport (CSIR 1997). A factor that does contribute to intentional overloading is the extent (length) of provincial road travel beyond that of unpaved forest roads (leaving forest roads and entering a provincial road). Provincial roads are relatively well policed and the prevalence of compulsory vehicle mass checks is an inhibiting measure, hence less overloading on provincial roads. However, although plantation roads are not private roads (access is open to the public), transport over plantation roads is not policed externally and therefore suggests

Table 3: Payload (percentage of legal load) by vehicle type and region

Region/payload	Mercedes-Benz 3340/45 (6×4) F/C	Nissan UD350 (6×4) F/C	MAN TGA 33.400 (6×4) BBL	MAN TGA 33.480 (6×4) BB	Volvo FH 13.400 (6×4) LTR
Region	Eastern Cape/ KwaZulu-Natal	Eastern Cape/ KwaZulu-Natal	Mpumalanga	Mpumalanga	Mpumalanga
Minimum	84	64	29	67	74
Average	103	125	102	99	100
Maximum	126	175	125	103	118
Loads overloaded (%)	59	95	3	0	17
Loads underloaded (%)	8	5	5	8	18

overloading to be intentional on the part of plantation company management. As a result, STT trucks over plantation roads are in general overloaded, particularly if the route does not involve a long stretch of travel over provincial roads, as in the case of Eastern Cape/KwaZulu-Natal.

It is well documented that loading trucks beyond the legal limit can cause damage to paved roads (CSIR 1997). Unsurfaced roads, as in the case of plantation roads, are also susceptible to increased damage, particularly the loss of gravel surfacing, creation of ruts, etc. (Jones 1984); it appears that this is at times overlooked in favour of larger (potentially illegal) loads. Although not the focus of this study, the financial impact of overloading and resultant lower travel speeds and of forest road damage and more frequent maintenance should be studied further.

Although VCI varied considerably on planation roads (very poor 15 to good 76), it did not play a part in the eventual model for speed prediction. This significance can perhaps be attributed to the fact that when travelling at lower speeds (as was found in the study), road condition does not play as large a role as when vehicles are travelling at higher speeds where the effect of potholes and corrugations, amongst others, will forcibly reduce speed for safety and driver comfort. This is confirmed by FERIC (1991), who found that speed ranges were narrower on lower standard (road surface condition) than on better road surface conditions. Potentially, the same can be said for gradient and vehicle power output. Although gradient was part of the data used in the analysis, it also did not play a role in speed prediction. In terms of truck power, the engine kilowatt rating seems sufficient to overcome grades in all cases but at the inherent overall slower speed maintained or achieved it was not significant to be considered in the prediction model.

Overall, the adjusted r^2 values for the model predicted roughly half of the variation in STT vehicle travel speeds (0.52). Although attempts were made to use representative drivers through a remote random selection process, the results suggest a human element in truck transport that was unaccounted for in this study as might be suggested with the high overloading issue in one region. This potential impact of different operators on the outcomes of STT efficiency was highlighted in the FERIC (1991) study. In their study, four drivers were evaluated in terms of the effect of their driving techniques on truck fuel consumption, speed variation, smoothness of gear change and gear selection, harsh braking and eventually optimal torque, with the intent to optimise fuel consumption and potential increased wear on truck components. All four drivers differed greatly in each aspect with both positive and negatives effects on STT productivity and efficiency. By increasing sample sizes and tracking more than one STT vehicle operation, the authors attempted to negate the influence of driver characteristics on the study.

Conclusions

The study developed a predictive model for travel speed for softwood STT over a range of forest and provincial roads of varying condition for the South African forest industry. Data were accumulated from both the Eastern Cape/KwaZulu-Natal and Mpumalanga forest regions of South Africa. These two regions provide the majority of the sawlog supply for the South African forest industry. Vehicle location and payload data were collected remotely using a combination of GPS tracking and remotely sensed data. Two STT contractors were selected from each forest region transporting pine sawlogs directly from compartment roadside landings to either a processing plant or log storage area. Five STT vehicle types, representative of transport operations in the two forest regions, were studied. Road surface condition was assessed for each identified road segment according to a VCI index. In addition, road width and the average gradient (%) for the road segment were also recorded.

Road class was discarded as a preferred indicator variable in favour of road width as the key predictor variable in that it provides a numerically continuous description of the relationship between the different road classes found on plantation road, it has a clear definition and is more easily measured. Due to the prevalence of loading STT vehicles beyond legal limits and to ascertain this effect on potential travel speeds, a percentage of the actual measured payload to the legal payload was calculated for inclusion in the eventual predictive model.

Of all the variables considered for the model, i.e. road width, gradient, road surface condition, vehicle maximum engine power and payload, the analysis showed that payload and road width were significant predictors of travel speeds. Principal component analysis was conducted to determine the degree of communality between the respective predictor variables, combining road width and VCI as one factor, and truck maximum power and the percentage of (legal) maximum payload as a second factor.

Comparisons of the correlations between average speed and the respective predictor variables showed that road width and percentage of maximum (legal) payload had the highest correlations. Multiple linear regression of these two factor variables were used in the model showing both variables as significant ($p < 0.05$) with an adjusted r^2 value of 0.52.

The study met its objectives as far as model development for predicting STT travel speeds. Future work should also be undertaken to determine both the financial impact of overloading and resultant lower travel speeds, and on the resulting forest road damage and increased maintenance frequency due to this overloading. Although attempts were made to use representative drivers through a remote random selection process, the results suggest a human element in STT transport that was unaccounted for in this study as suggested by an adjusted r^2 value that explained roughly just over half of the variation. The prevalence of overloading is also possibly an indication of an unaccounted human effect. Further work is needed to better assess the magnitude of the human element and to validate the developed predictive model and to improve its predictive ability.

Acknowledgements — The authors acknowledge the following organisations and individuals for assisting with this project: the South African forest industry, the transport contractors for providing tracking data, and UBC exchange students Cynthia Lu, Sam Field and Debbi Leung, who assisted with data capture and analysis.

References

Byrne JJ, Nelson RJ, Googins PH. 1960. *Logging road handbook: the effect of road design on hauling costs*. Handbook no. 183. Washington, DC: US Department of Agriculture.

Chong GJ, Wrong, GA. 1989. *Manual for condition rating of gravel surface roads.* Ministry of Transportation Ontario SP-025. Downsview, Ontario: Ministry of Transportation Ontario.

CSIR (Council for Industrial and Scientific Research). 1997. *The damaging effects of overloaded heavy vehicles on roads* (4th edn). Pretoria: CSIR.

Department of Environmental Affairs. 1982. Beleid insake konstruksie van paaie op staatsbosse. Forest Management Instruction no. 5/3/1 of February 1982. Unpublished report. Pretoria: Department of Environmental Affairs.

Department of Transport. 1994. Draft TRH 22: Pavement management systems. Pretoria: Department of Transport.

Devlin GJ, McDonnell K, Ward S. 2008. Timber haulage routing in Ireland: an analysis using GIS and GPS. *Journal of Transport Geography* 16: 63–72.

Devlin GJ, McDonnell K. 2009. Assessing real time GPS asset tracking for timber haulage. *The Open Transportation Journal* 3: 78–86.

Falls LC, Landers S, Bekheet W, Fredrickson R. 2003. Implementation of the British Columbia side road assessment plan. *Transportation Research Record* 1819: 262–266.

FERIC (Forest Engineering Research Institute of Canada). 1991. Tractor-trailer productivity and efficiency. Companion text for FERIC Seminar. XXXXX: FERIC.

FSA (Forestry South Africa). 2011. Abstract of South African forestry facts for the year 2010/2011. Rivonia: Forestry South Africa.

Groves KW, Pearn GJ, Cunningham RB. 1987. Predicting logging truck travel times and estimating costs of log haulage using models. *Australian Forestry Journal* 50: 54–61.

Kennedy JA. 1986. *Standards for logging roads*. *Logging Industry Research Association Technical Release* 8(7). Rotorua: Logging Industry Research Association.

Jackson RK. 1986. Log truck performance on curves and favorable grades. MSc (Forest Engineering) thesis, Oregon State University, USA.

Jackson RK, Sessions J. 1987. Logging truck speeds on curves and favorable grades of single-lane roads. *Transportation Research Record* 1106: 112–118.

Jones D, Paige-Green P. 2000. Draft TMH12: Pavement management systems: Standard visual assessment manual for unsealed roads (version 1). Pretoria: CSIR Transportek.

Jones TE. 1984. The Kenya maintenance study on unpaved roads: research on deterioration. TRRL Laboratory Report 1111. Crowthorne: Transport and Road Research Laboratory, Department of the Environment, Department of Transport.

Morkel R. 1994. The management of South African forest roads in perspective. BSc(Hons) thesis, University of Stellenbosch, South Africa.

Prisley SJ, Carruth SJ. 1995. GPS speeds data collection on GIS road networks. Paper presented at ESRI User Conference, 22–26 May 1995, Palm Springs, California.

RSA (Republic of South Africa). 1996. National Road Traffic Act (Act No. 93 of 1996). *Government Gazette, South Africa* 1892(17603).

Saskatchewan Highways and Transportation. 2001. Surface condition rating manual gravel surface. Regina, Saskatchewan: Department of Highways and Infrastructure.

SANRAL (South African National Roads Agency Limited). 2003. Geometric design guidelines. Available at http://www.nra.co.za/live/click.php?u=//sanral.ensight-cdn.com/content/GDGGeometricDesignGuide.pdf&o=Item%2B233&v=814d8c [accessed 23 May 2014].

SANRAL. 2012. South African classification and access management manual. Technical Report for Highways no. 26. Pretoria: SANRAL.

Simwanda M. 2010. Modelling biomass transport on single lane forest roads and monitoring GPS accuracy for vehicle tracking under different forest canopy conditions. MSc (Forest Engineering) thesis, Oregon State University, USA.

US Department of the Army. 1995. Unsurfaced road maintenance management. Technical Manual no. 5-626. Washington, DC: Headquarters, Department of the Army.

Uusitalo J. 2010. *Introduction to forest operations and technology*. Tampere: JVP Forest Systems.

van der Gryp A, van Zyl G. 2007. Variability and control of gravel road visual assessments. *Transportation Research Record* 1989: 247–253.

Walker D. 2002. Pavement surface evaluation and rating: gravel roads manual. Madison: Wisconsin Transportation Information Centre, University of Wisconsin-Madison.

Received 10 November 2013, revised 27 June 2014, accepted 13 July 2014

Chapter 6: An Eastern Cape Softwood Sawtimber Supply Chain Case Study

Pierre A Ackerman*, Reino E Pulkki*' ** and Elizabeth Gleasure* (under review by Southern Forests: A Journal of Forest Science)

* Department of Forest and Wood Science, Stellenbosch University

Private Bag X1, Matieland. South Africa.

**Faculty of Natural Resources Management, Lakehead University. 955 Oliver Road, Thunder Bay, Ontario, Canada

Corresponding author, e-mail: packer@sun.ac.za

Abstract

Supply chain principles were analysed by investigating the effects of smaller scale and incremental interventions in a forest to mill value chain on financial returns and forest resource use in an Eastern Cape case study area. Three previous studies provided input by determining fibre balances, a terrain factor and primary and secondary transport travel speeds and efficiencies. Network analysis, combined with pixel-based GIS, analysed different primary and secondary transport scenarios. The forest road network was repeatedly refined through decommissioning and selected upgrades, and the timber resource flowed over the network to the mill. With sequentially improved secondary transport travel speeds, primary transport efficiency and fibre use, the net financial returns of the various scenarios were determined by applying discounted cash flow analysis. To address all possible combinations, 144 unique scenarios were created. The best annual return achieved was R300.8 million associated with a highly upgraded road network and associated fast secondary transport speeds, cable skidder extraction, motor-manual felling and cross-cutting at merchandising yard, all factors at optimal performance. The lowest return was R40.4 million (simplified road network, low secondary transport speeds, cable skidder extraction, mechanised felling, roadside merchandising and at *status quo* systems performance). Examination of individual factors found that systems performance, secondary transport speeds and road network had the greatest influence, with systems performance and fibre losses, providing the largest impact. Secondary transport speed followed as nine of the top ten Net Present Value scenarios were able to achieve with the highest possible road design speeds. Higher class networks consistently outperformed the baseline and simplified scenarios. Harvesting system had limited effect. When operating at peak performance, merchandising yard merchandising becomes a better choice. There was no clear difference in terms of felling method or skidder type. It is clear that the optimised use of potentially the most productive machine for example in one system does not provide the best final results and that it is the basic harmonisation of all factors that must be taken into account. As in all three previous studies and related studies the human element plays a large part.

Introduction

With increasing globalisation, the forestry industry is under constant pressure to improve efficiency of forest operations and resource use as well as to reduce costs of and within the value chain. The forest industry has begun to see potential gains coming from improved integration between firms acting as different parts of the supply chain (Carlsson and Rönnqvist 2005). Supply chain management (SCM) argues that to make the greatest gains, firms can no longer operate solely as individuals, but rather as entire supply chains focused on the final customer demand (Pulkki, 2001). It has been speculated that in the future it will no longer be individual firms competing, but rather supply chains as a whole (Poirier, 1999).

The South African forest industry produced 18.5 million m^3 of roundwood from industrial forest plantations in 2010 (FSA 2011). Of this, around 4.5 million m^3 is softwood roundwood bound for sawtimber production annually (FSA 2011). Given the magnitude of this sector of the South African forestry industry, examining the supply chain from forest to mill and finding avenues to improve resource use and increase potential value is essential. One key consideration surrounding SCM is that sub optimisation within the value chain cannot alone be considered valid, as gains made further down the chain may become non-existent, or even detrimental when considered at the supply chain level (Pulkki 2001). In other words, small changes at one level, while considering others, which may be beneficial, can have greater outcomes than anticipated.

Given the importance of SCM as a business strategy and the importance of softwood sawtimber roundwood as a product to the South African forest industry, understanding the interactions at various stages of the value chain are considered in this study. In order to examine these interactions, a case study using a typical softwood roundwood plantation over a 30 year rotation by applying net present value analysis in the Eastern Cape province of South Africa is analysed. The objectives of this study is to determine potential gains that can be expected through incremental upgrading of the existing forest road network, considering different felling and extraction scenarios, improving efficiencies of both primary and secondary transport and reducing fibre losses along the value chain over a 30 year period, given the additional silvicultural and management costs.

Materials and Methods

Study Area

A forest estate located in the Eastern Cape Province of South Africa consisting of 16 345 ha and approximately 820 km of forest roads roughly producing between 171 000 m^3 and 184 000 m^3 of roundwood was used as a case area for this study. The plantation feeds sawlogs to a single sawmill located on the estate that is centrally located but in close proximity to the southern boundary of the estate.

Network analysis and Supply Chain Analysis

This SCM case study analysis is based on the outcomes of three previous studies (Ackerman and Pulkki 2012, Ackerman et al 2014, Ackerman et al 2015) in which fibre balances, a terrain factor, primary transport travel speeds and efficiency, as well as secondary transport travel speeds and transport efficiencies in pine sawtimber timber harvesting and transport systems were studied. The outcomes of these three studies are related and preparatory to this case study, including its timber resource, harvesting systems and road network. A combined network analysis model and pixel-based geographic information system (GIS) is used to analyse a number of primary and secondary transport scenarios within the case study area. The network analysis pixel based GIS is as outlined in Pulkki (1996) and Ackerman and Pulkki (2004). This study required the current forest road network to be repeatedly refined through road decommissioning and selected road upgrades and the timber resourced flowed over the network to the processing plant. With sequentially improved travel speeds of the secondary transport, improving skidder efficiency and improved fibre use (reduced fibre losses), it is possible to quantify the net financial return of the various projects (scenarios), production costs and timber resource use. SCM principles were analysed by investigating the effect that the smaller scale and incremental interventions would ultimately have on the returns to the estate over a 30 year period (one full rotation), applying discounted cash flow financial analysis through the supply chain from forest to mill.

Forest Road Network Scenarios

Apart from the current forest road network, three further unique road network scenarios were developed for the estate. In this case, Scenario 1 describes the baseline and current spatial layout and road classes of the existing road network (Table 1). Scenario 2 was created by simplifying scenario 1. Roads were eliminated (with preference given to the lowest class of road) to maintain an average extraction distance between 100 m and 125 m, suitable to skidder extraction systems (MacDonald, 1999). Deactivated roadway areas are subsequently afforested at year one. The additional 24.4 ha and subsequent volume gained through deactivation will be harvested at year 30.

Scenarios 3 and 4 each take Scenario 2 a step further as they both include road upgrades (increasing road right-of-way). As mentioned above, road upgrades are assumed to be completed in equal portions per year over the one full rotation. As road upgrades imply increasing road right-of-way width given the individual road class standards, there is an associated loss in plantation area. It is assumed that the consequences of the loss of area would not be felt until year 30 as the increased area earmarked for road upgrades would be harvested prior to the road upgrade and this volume would still be consistent with the annual harvesting plan until year 30 is reached and the upgrades are completed.

Scenario 3 therefore takes scenario 2 a step further and upgrades all class C roads to class B. While the deactivated areas in scenario 2 could be considered a gain in planted area, the increase in road right-of-way width for Scenario 3 leads to a gross area loss of 64.33 ha over 30 years, or a net loss of 39.9 ha over 30 years. Scenario 4 takes scenario 2 further and upgrades all class C roads to class B and all class B roads from Scenario 2 to class A. While the deactivated areas in Scenario 2 could be considered a gain in planted area, the increase in road right-of-way for Scenario 4 leads to a net loss of 115.75 ha over 30 years.

Table 1: Summary of different road network scenarios considered.

Scenario	Description	Road Density (m ha^{-1})	Net changes at year 30 (ha)
1	Baseline scenario. Existing road network used.	49.9	0
2	Road network reduction scenario. Road network thinned keeping average extraction distance to between 100 and 125 m.	45.6	+24.4
3	Upgrade of Class C to Class B roads in addition to road network reduction in scenario 1. Scenario 2 sees Class C roads upgraded to Class B.	45.6	-39.9
4	Upgrade of Class B to Class A and Class C to Class B in addition to road network reduction. Scenario 2 sees Class B roads upgraded to class A and existing Class C roads upgraded to Class B.	45.6	-115.75

Secondary Transport Speeds

Three levels were considered for secondary transport travel speeds. Level 1 used respective road class average travel speeds as found for maximally, but legally loaded trucks, as described by Ackerman et al. (2015). Level 3 assumed trucks would be operating at or close to the design speeds of the respective road classes as described by the National Road Transportation Authority (SANRAL, 2012). Level 2 was hypothetically created, which set travel speeds for the respective road classes between Scenarios 1 and 2. Table 2 summarizes the road speeds used for each scenario.

Table 2: Comparison of road travel speeds for the different road speed scenarios.

Level	Road Travel Speeds (km h^{-1})							
	Unloaded				Loaded			
	Provincial	A	B	C	Provincial	A	B	C
1	45.6	28.1	20.6	15.6	39.5	22.0	14.5	9.5
2	60.0	45.0	30.0	20.0	55.0	40.0	25.0	15.0
3	80.0	60.0	40.0	30.0	75.0	55.0	35.0	25.0

Trucks were assumed to be loaded to legal capacity according to Regulation 241 (RSA 1996). A typical truck for the case study was used and its legal payload is 32.0 m^3. This load size was used across all scenarios.

Timber harvesting, primary and secondary transport and fibre losses

Six harvesting scenarios are applicable to this case study (Figure 1). Each of these systems is applied to each road scenario. Specific felling methods, merchandising locations and loading sequences are shown for each system. Harvest system can be considered a 2x2x1.5 factorial design with factors being merchandising location (roadside or merchandising yard), skidder type (cable or grapple) and felling type (motor-manual or mechanised). Typically this would produce a 2x2x2 design; however, because grapple skidders require their loads to be pre-bunched, a motor-manual felling operation for grapple skidders was not considered feasible and this treatment was abandoned. As a result, for grapple skidders only mechanised felling was considered and hence resulting in the 2x2x1.5 design. .

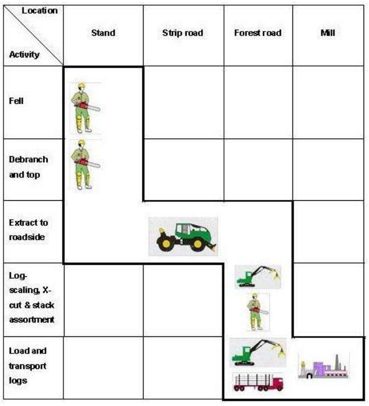

Figure 1a: Motor manual felling, cable skidder extraction and roadside landing merchandising.

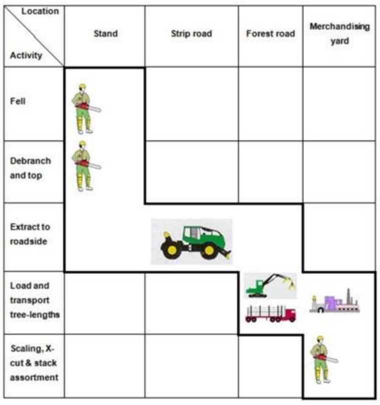

Figure 1b: Motor manual felling, cable skidder extraction and merchandising yard merchandising.

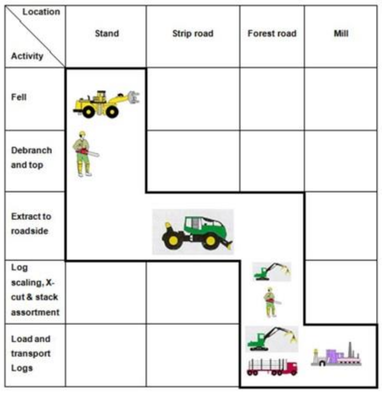

Figure 1c: Mechanised felling, cable skidder extraction and roadside landing merchandising.

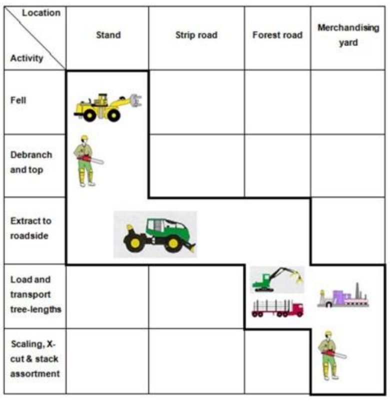

Figure 1d: Mechanised felling, cable skidder extraction and merchandising yard merchandising.

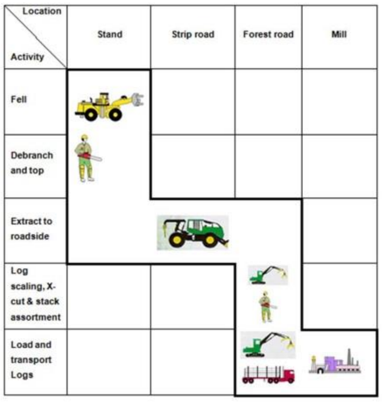

Figure 1e: Mechanised felling, grapple extraction and roadside landing merchandising.

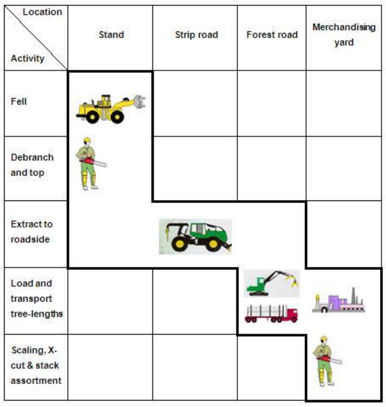

Figure 1f: Mechanised felling, grapple extraction and merchandising yard merchandising.

Fibre losses (Table 3) for each system are determined by including losses related to felling saw kerf, stump residues, tops not extracted, crosscut saw kerf, log allowance, excessive removal and incorrect log allowance. These values are defined in and taken from Ackerman and Pulkki (2012). The productivity, travel speeds (loaded and empty) and load volumes for the skidder types (Table 3) are based on the study done by Ackerman et al. (2014). Since wander ratio was not found to vary, 1.12 (Ackerman et al. 2014) was used as the wander ratio value for extraction across all scenarios. Centralised merchandising location is located at the mill for this study as opposed to roadside landing merchandising under the assumption that the necessary infrastructure and physical space is available.

Table 3: Description of fibre losses and skidder properties used for each harvesting system examined (Ackerman and Pulkki 2012).

Merchandising Location	**Roadside merchandising**			**Merchandising at Merchandising Yard**		
Felling Method	Manual	Mechanised	Mechanised	Manual	Mechanised	Mechanised
Skidder Type	Cable	Cable	Grapple	Cable	Cable	Grapple
Fibre Losses (%)						
Felling Saw Kerf	0.15	0.94	0.94	0.15	0.94	0.94
Stump Loss	0.85	0.43	0.43	0.99	0.42	0.42
Top Loss	2.84	2.18	2.18	3.13	2.18	2.18
Crosscut	0.22	0.21	0.21	0.17	0.17	0.17
Log Allowance	1.47	1.84	1.84	1.66	1.466	1.466
Excessive Removal	1.56	0.48	0.48	2.47	2.47	2.47
Incorrect Log Allowance	0.45	1.29	1.29	0.45	0.24	0.24
Total	7.54	7.37	7.37	9.02	7.87	7.87
Skidder						
Speed Empty (km h^{-1})	7.91	7.91	6.23	7.91	7.91	6.23
Speed Loaded (km h^{-1})	6.96	6.96	5.90	6.96	9.96	5.90
Load Volume (m^3)	2.53	2.53	5.67	2.53	2.53	5.67
Productivity (m^3 h^{-1})	20.7	20.7	123.9	20.7	20.7	123.9
Operating Cost (with operator) (R h^{-1})	1519.00	1519.00	1847.00	1519.00	1519.00	1847.00

Fibre loss and the impact on final mill delivered volume are calculated by accounting for changes in extraction and secondary transport volumes depending on the fibre losses at each stage in the supply chain (e.g., fibre losses at felling affect extracted volume, fibre losses at roadside merchandising affect volume of wood to transport, and so on and so forth). This process is described in Figure 2.

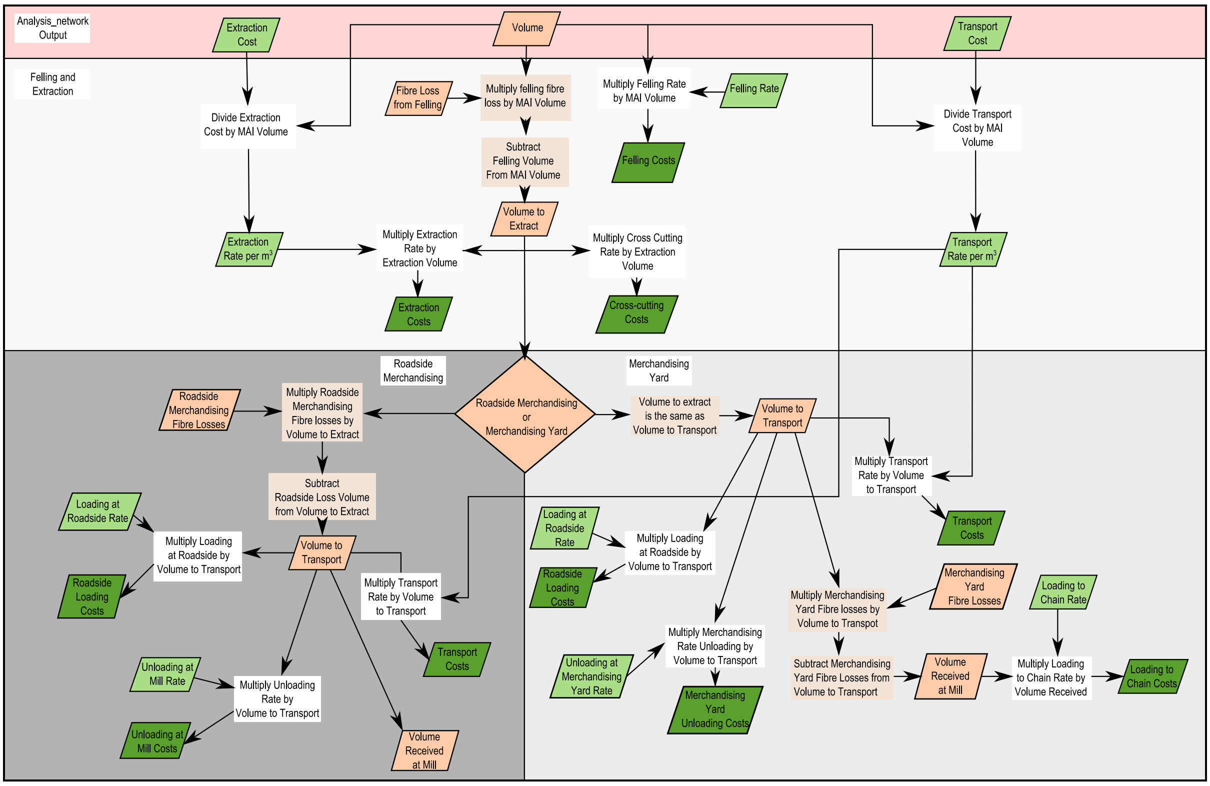

Figure 2: Flowchart demonstrating how final harvesting costs and mill delivered volumes were determined depending on merchandising yard location. Roadside merchandising is on the lower left and merchandising yard on the lower right.

Since for road network scenarios 2, 3 and 4 at year 30, volume would be different than the initial volume, the adjusted volumes are used as the input volume for the process described above and then the final mill delivered volume and harvesting costs were recorded for year 30.

Performance

Considering that Ackerman and Pulkki (2012) found larger fibre losses resulting from poor method (e.g. stumps 7 cm on average higher than acceptable) and Ackerman et al. (2014) found that skidders, particularly cable skidders, were able to improve productivity, it was decided that it would be worthwhile to model improved performance. To keep the number of scenarios at a manageable level, it was assumed that when extraction performance was optimal, fibre losses would also be minimised. This assumption is based on the concept that an operation running with optimal operational and skidder performance would likely also have the adequate supervision capacity and control mechanisms in place to minimise fibre losses through the systems (Table 4).

Table 4: Productivity and travel speeds for cable and grapple skidders depending on performance.

Extraction Machine	Cable Skidder		Grapple Skidder	
Performance level	Non-optimal	Optimal	Non-optimal	Optimal
Productivity (m^3/h^{-1})	20.7	49.4	123.9	137.0
Speed Empty (km h^{-1})	7.91	7.91	6.23	6.23
Speed Loaded (km h^{-1})	6.96	6.23	5.90	4.32

While it would have been quite simple to run a scenario for each change, the fundamental principle of supply or value chain management is that small changes can have a far-reaching effect. As a result, the interactive effect of all changes was studied. This led to the creation of 144 individual and unique scenarios.

Additional operational inputs

As the network analysis model calculates cost of primary and secondary transport, it is necessary to include other related costs for felling and timber preparation, as well as those of merchandising at the two locations, loading, offloading and the cost of moving wood from the merchandising areas at the mill to the mill in-feed systems (Table 5).

Table 5: Additional systems input costs

Full-tree grapple skidder extraction to roadside and transport to merchandising yard		**Tree-length cable skidder extraction to roadside and transport to processing plant**	
Fell (R m^{-3})	19	Fell, debranch and top (R m^{-3})	15
Debranch at roadside (R m^{-3})	10		
Merchandising at merchandising yard (R m^{-3})	9	Merchandising at roadside (R m^{-3})	12
Loading at roadside (R m^{-3})	18	Loading at roadside (R m^{-3})	24
Unloading at merchandising yard (R m^{-3})	12	Unloading to in-feed chain (R m^{-3})	15
Loading to feed chain at mill (R m^{-3})	25		
Truck load volumes (m^3)	32	Truck load volumes (m^3)	32
Truck rate with operator (R h^{-1})	1 050	Truck rate with operator (R h^{-1})	1 150

Calculation of Annual Revenues and Costs

Calculation of Annual Volumes and Harvesting Costs

Determining volume prior to felling, extraction and transport costing was done using a network analysis program developed by Pulkki (1984), Pulkki (1996), and applied in Ackerman and Pulkki (2001), Ackerman and Pulkki (2002) Ackerman and Pulkki (2004). Both the forest cover map and the road network grids were converted to the appropriate raster format for the network analysis as described by Ackerman and Pulkki (2001). The network analysis programme uses a network optimisation algorithm (Taha 1982, Dykstra 1984, Pulkki 1984) to assign the individual forest cover cell to the closest road cell (primary transport) with the shortest secondary travel time to the user specified mill cell. The network analysis programme allows for customisation of secondary transport speeds, load sizes, extraction speeds, machine and truck costs and load sizes. Volume is calculated by summating the total area by species (in this case study, only softwood pine) and multiplying by the average Mean Annual Increment (MAI) for the estate. An average MAI of 12 m^3 ha^{-1} yr^{-1} was used based on a weighted average of the individual compartment MAI and weighting by compartment area before translating the grid into raster format. This volume therefore represents the available and utilisable volume annually prior to harvest. Fibre losses were then deducted from this value utilising the procedure described in Figure 2.

Road Maintenance and Upgrades

For road scenarios one (baseline) and two (simplified), road maintenance cost was charged at R107.09 ha^{-1} of forest cover area. This worked out to an annual total cost of R1 750 386.05. For road scenarios three and four, the road maintenance cost was assumed to instead be used to upgrade a section of the road network annually. Since the width (Brink 2005) added to the road right-of-way width when upgrading to a Class B road from a Class C road is only 2 m (Class C roads have a width of 3 m and Class B roads have a width of 5 m) (SANRAL 2003), whereas to upgrade from a Class B to a Class A road is 3 m (Class A roads have a width of 8 m), the costs were higher. The rate per km to upgrade a class C to Class B road was R20 000.00 km^{-1} and to upgrade a Class B to a Class A road was R 40 000.00 km^{-1}. In total, scenario 3 had an annual road upgrade cost of R214 433.00 and scenario 4 was R551 500.00 (Forest Economic Services 2013).

Associated Establishment and Additional Silviculture and Management Costs

Silviculture, tending and management costs for the existing stands were calculated based on data from the Forestry Economics Services (2013) and were R172.18 m^{-3} of wood delivered, which equates to R1 983.25 ha^{-1}. For the first (baseline) road scenarios, this was assumed to remain constant throughout the duration of the project and amounted to a total annual cost of R32.4 million.

For the second road network scenario (deactivation), it was assumed that in the first year establishment would begin on the previously road based areas (24.4 ha). Across the 30 year project duration, costs for protecting and managing this additional area including weeding (tending), protection, thinning were considered and added to the yearly total silviculture cost.

For the third and fourth scenarios, given that the road upgrades were systematically decreasing the planted area, the silviculture costs were appropriately scaled down given the annual area lost.

Calculation of Annual Revenues

To best show the gains in revenue from the implementation of the various supply chain improvements, mill delivered wood cost was used to calculate revenues. Based on Forestry Economics Services (2013), the average mill delivered price for pine sawtimber was R312.21 m^{-3}.

Each year's delivered wood volume (annual MAI less volume fibre losses) was multiplied by this price to give annual revenue.

Discounted Cash Flow Analysis to Calculate Net Present Value (NPV)

Annual cost of wood volume delivered to the mill was calculated for each of the 144 individual scenarios, providing a finite annual and present value cost of wood delivery. This would have allowed direct comparison of values. However, other costs, such as road deactivation and upgrading, cannot feasibly be executed to completion in one year or year one; they are phased in over a period of time, preferably over one rotation of 30 years as in this case.

A common technique for evaluating the net benefit of a project is Net Present Value (NPV) (Bullard and Straka, 2011). This is done by discounting all of the projects' revenues and costs to the present and then calculating the difference between the two (net value). This technique is typically referred to as discounted cash flow analysis (Ham and Jacobson, 2012). In other words, to achieve a true reflection of costs and income, both costs (timber preparation, primary and secondary transport and merchandising, silviculture and management) and revenue (timber sales to mill) per year for 30 years are discounted back to year one.

Each year's respective costs and revenues are therefore discounted back to the present using a real interest rate of 4%; assuming a lending rate of 10% and an inflation rate of 6% (Bullard and Straka, 2011). The lending rate and PPI are based on actual figures over the last 10 years (2005 – 2015) from Statistics South Africa (Statistics South Africa, 2015). These discounted values were then summated to produce the NPV of the project. NPVs were then compared. A large NPV is "better" (more value is gained over time) than a small NPV (Bullard and Straka, 2011) and therefore, the scenario producing the largest NPV is considered the most likely to have the greatest financial payback.

Statistical Analysis

Due to the large number of scenarios, creating an easy way to visualize the associated gains and losses is complex. The scenario design was effectively a 4 x 3 x 6 x 2 design but with only one output value for each scenario. As a result, conducting a classical factorial analysis to compare the interaction of all 4 factors was not appropriate. We can note that there is an individual effect for each scenario, and a simple one way ANOVA for the road network and road speed options as well as t tests for independent groups was conducted for each variable.

Results

Net Present Value

These values ranged dramatically across the 144 scenarios, ranging from approximately R40 million to R300 million. Mean NPV was approximately R180 million. The highest NPV scenario was with road network four, fast secondary transport speeds, motor-manual (MM) felling (as opposed to mechanised felling), cable skidder extraction, merchandising yard merchandising, all at optimal performance levels. Table 4 shows the highest and lowest ranked NPV's.

Table 4: Top 10 highest (and lowest) NPV scenarios (Merch = merchandising location; RS = roadside, MY = Merchandising yard)

Rank	Road Network Scenario	Transport Speed Level	Harvest System			Performance	30 Year NPV (Million)	Average Annual Volume (m^3)
			Skidder Type	Felling	Merch			
1	4	3	Cable	MM	MY	Optimal	R 300.8	184 503
2	3	3	Cable	MM	MY	Optimal	R 300.7	184 531
3	4	3	Grapple	Mech	MY	Optimal	R 295.8	183 401
4	3	3	Grapple	Mech	MY	Optimal	R 295.7	183 429
5	4	3	Cable	Mech	MY	Optimal	R 292.2	183 401
6	3	3	Cable	Mech	MY	Optimal	R 292.1	183 429
7	4	3	Cable	MM	RS	Optimal	R 278.7	184 762
8	3	3	Cable	MM	RS	Optimal	R 278.2	184 791
9	1	3	Cable	MM	MY	Optimal	R 271.9	184 546
10	4	2	Cable	MM	MY	Optimal	R 271.9	184 503
-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-
135	1	1	Grapple	Mech	RS	Normal	R 73.4	174 658
136	2	1	Grapple	Mech	RS	Normal	R 69.8	174 667
137	1	1	Cable	Mech	MY	Normal	R 66.2	173 717
138	2	1	Cable	Mech	MY	Normal	R 61.1	173 726
139	1	1	Cable	Manual	MY	Normal	R 60.5	171 676
140	2	1	Cable	Manual	RS	Normal	R 55.3	171 685
141	1	1	Cable	Manual	RS	Normal	R 47.9	174 330
142	1	1	Cable	Mech	RS	Normal	R 45.6	174 658
143	2	1	Cable	Manual	RS	Normal	R 42.7	174 339
144	2	1	Cable	Mech	RS	Normal	R 40.4	174 667

Because only one NPV was produced for each of the 144 separate scenarios, a complete 2x3x6x2 factorial ANOVA was not possible. Examination of the individual factors found that the road network, secondary transport speeds and performance were significant. Harvest system was not found to be significant.. No significant effect was observed for felling method, or skidder type or the combination of the factors; however, merchandising location was found to be significant.
After eliminating harvest system as a potentially significant factor, a factorial ANOVA of road network, transport speed and performance was done. The three way interaction and the respective two ways interaction was not significant and therefore the main effects were examined (Milton and Arnold, 1999). All three main effects were significant. Table 5 summarises factors and Figures 1 through 4 below show the relationships.

Table 5: Summary of the factors and their respective significance.

Factor		p Value	Significance
Road network		0.019	*
Transport speeds		0.000	***
Harvest system		0.329	NS
	Merchandising Location	0.039	*
	Felling Method	0.763	NS
	Skidder Type	0.247	NS
Performance		0.000	***

Road Network

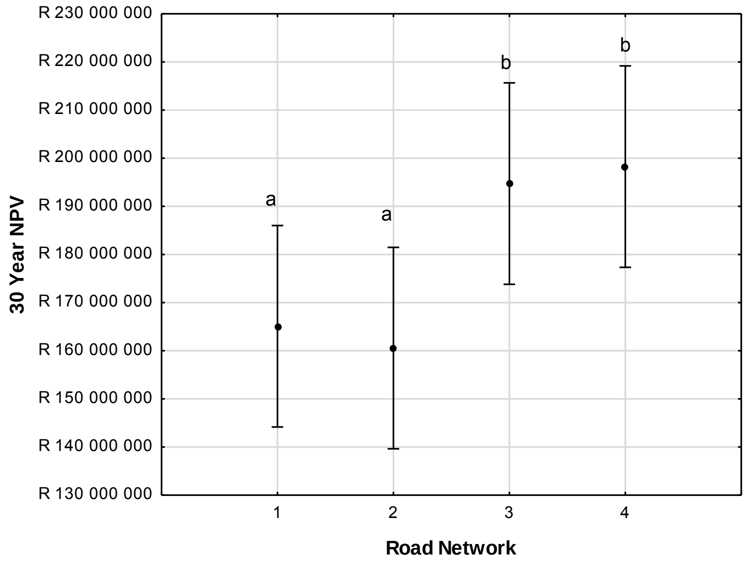

Figure 1: Comparison of 30 year NPV based on road network scenario.

Road network scenarios 1 and 2 (“a”) were not found to differ significantly from each other. Scenarios 3 and 4 (“b”) were also not found to differ significantly. Scenario 3 and 4 had significantly ($p < 0.05$) higher NPVs than scenarios 1 and 2 and therefore were associated with greater value.

Transport speeds

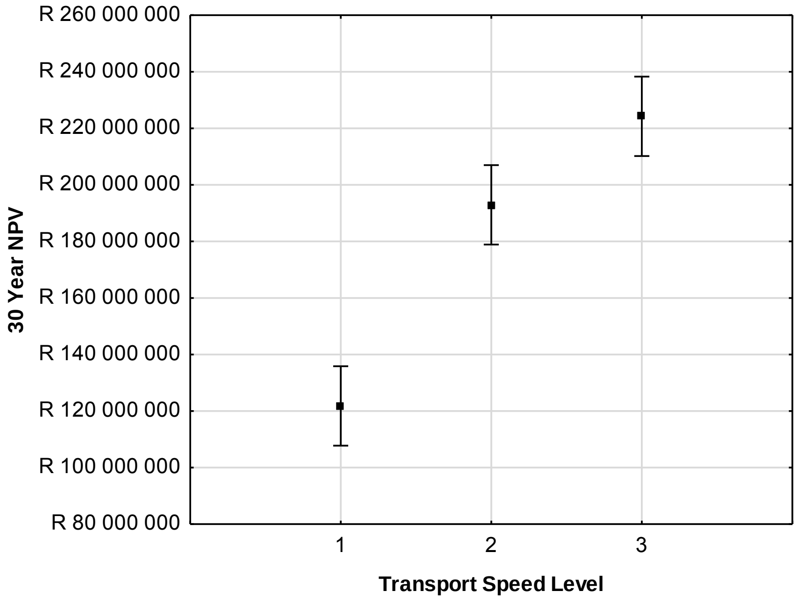

Figure 2: Comparison of 30 year NPV based on transport speed level.

All three transport speed levels were found to vary significantly in terms of NPV. Level 1 was very highly significantly ($p < 0.000$) slower than level 2 and level 3. Level 2 was highly significantly slower than level 3.

Merchandising locations

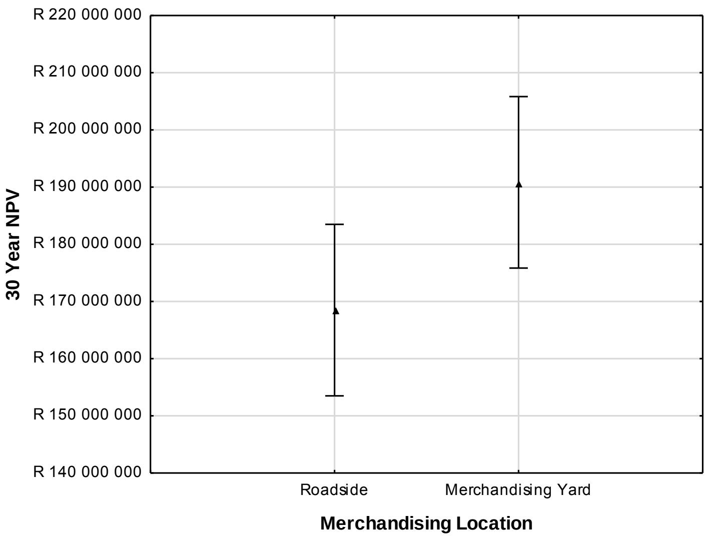

Figure 3: Comparison of NPV depending on merchandising yard location.

Merchandising at merchandising yard was significantly ($p < 0.05$) different than merchandising at roadside.

Performance

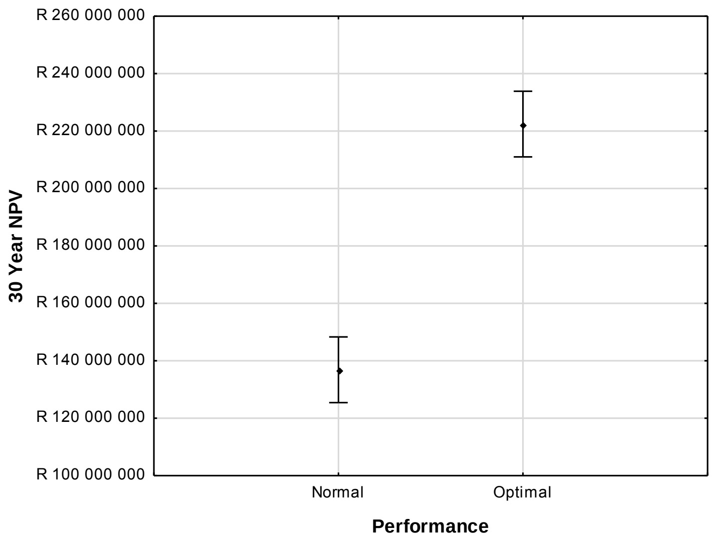

Figure 4: Comparison of 30 year NPV based on performance level.

Non-optimal performance was very highly significantly lower than optimal performance.

Volume

Average annual mill delivered volume varied from 171 635.81 m^3 yr^{-1} to 184 815.94 m^3 yr^{-1}. Interestingly, the highest potential annual achievable average volumes were not from the same scenarios as the highest NPV (Table 4). In fact, the correlation between average annual volume (m^3 yr^{-1}) and NPV was 0.66, indicating a strong relationship, but not a perfectly proportional one. Figure 5 below shows a scatterplot of this relationship with higher volumes generally indicating a higher NPV.

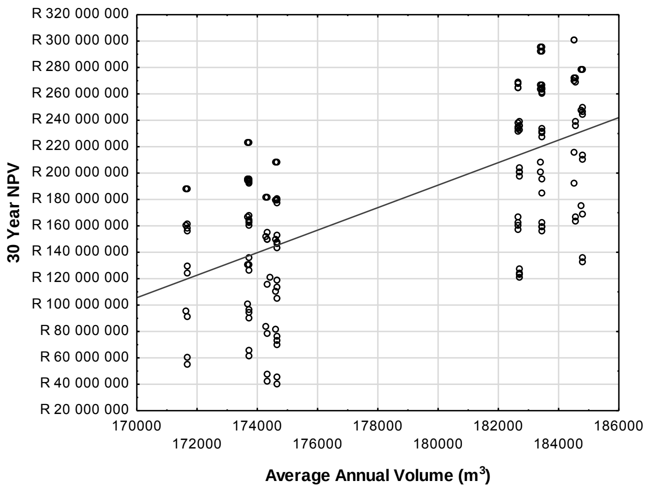

Figure 5: Scatterplot of the relationship between average annual volume (m^3) and 30 year NPV. The two variables are positively correlated at 0.66.

Neither road network nor secondary transport speeds were found to affect volume. Harvest system was also not significant nor was the individual harvest system factors of felling method, skidder type or merchandising location. The three way interaction between combined skidder type and felling method; merchandising location and performance was very highly significant ($p < 0.001$) and is shown in Figure 6.

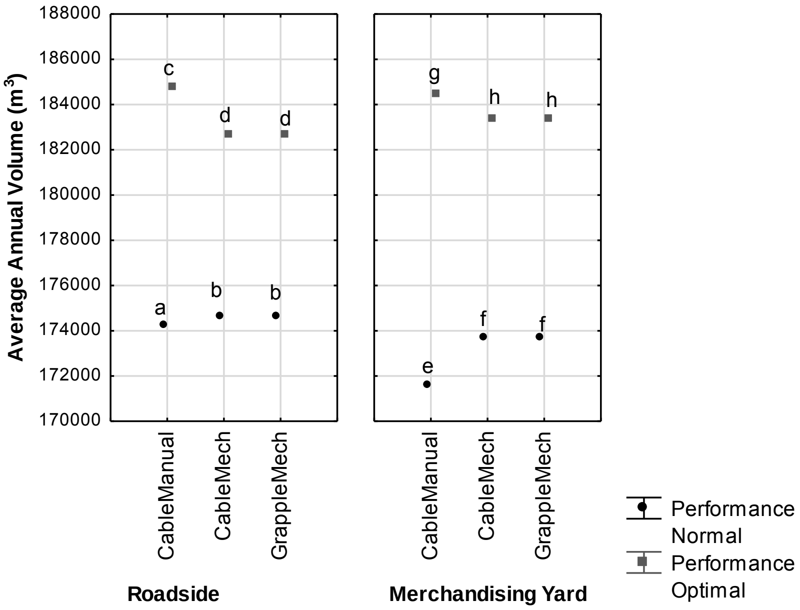

Figure 6: Factorial ANOVA comparing merchandising location; combined felling method and skidder type; and performance. Similar groups are marked with the same letter.

The largest gains in average annual volume, regardless of merchandising location were the cable extraction with motor-manual felling. Mechanised felling, regardless of skidder type were the same depending on merchandising location and performance.

Costs and Revenues

Average annual harvesting costs ranged from approximately R 7.9 million to R 18.0 million. The lowest harvesting costs were associated with eight of the top ten highest net NPV scenarios (Table 4). Average annual silviculture costs ranged from approximately R32.3 million to R32.4 million. The lowest silviculture costs were associated with five of the top ten highest net NPV scenarios. Average annual revenue ranged from approximately R53.6 million to R57.7 million. Only two of the top ten highest NPV scenarios were associated with the highest average annual revenues.

Discussion

The interplay between higher revenues, lower costs, and greater volumes combine to produce the best scenario. Higher volume alone through reduced fibre losses does not produce the highest NPV as, although a harvest system may be functioning at an optimal level, if the road network does not support higher secondary transport speeds or the trucks themselves drive at baseline level one speeds, these additional costs will negate the benefit of greater volumes. The reverse also applies; a faster road network with poor harvest system performance will also produce a lower value. Ultimately, the combination leads to the best outcome (Pulkki 2001).

Considering that improving every aspect of the supply chain at once becomes difficult, it is worthwhile to assess which of the factors alone has the greatest impact. By far, this was the performance factor. Reducing unnecessary fibre losses has the benefit of wasting less fibre and therefore delivering greater volume to the mill resulting in increased revenue (Ackerman and Pulkki 2012). Even systems which were associated with lower volumes (e.g. motor-manual felling, cable skidder extraction, roadside merchandising) can make significant gains when the fibre losses are mitigated. Indeed, as shown in Figure 6, the semi-mechanised (MM felling and cable skidder extraction) systems have the greatest ability to improve.

Secondary transport speed was the second most important factor, as nine of the top ten NPV scenarios utilised the level 3 transport speeds; that is, travelling close to the recommended speed for the roads. Faster transport leads to quicker return times and better utilisation of the trucks themselves (potentially more loads per shift). Considering that transport alone is one of the largest costs (Pulkki 2001), any effort made to improve transport efficiency logically will increase value. The importance of a well maintained and efficient (upgraded) road network is therefore of significant importance.

Road networks were the third most important element, with the higher class networks consistently outperforming the baseline and simplified scenarios (one and two, respectively). There is a high degree of collinearity between secondary transport speeds and road networks. Higher class roads are typically wider and designed for higher speed limits, and therefore provide the ability for the truck to reach greater speeds (Morkel 1994). Despite the long duration of implementing upgrades and the costs associated, it would appear generally that if a road network can be designed with fewer roads of a higher class, the gains significantly outweigh the costs of implementation (Ackerman and Pulkki, 2001). Associated silviculture and management costs were in fact much higher than annual maintenance and road implementation costs when considered across the lifetime of the project. A change in interest rate could potentially impact these outcomes; however, considering the significant increase in value associated with the higher transport speeds on higher road classes, this potentially dissipates the effect of small changes in interest rates. Finally, any change in interest rate would also create changes throughout the supply chain as interventions at one level can have repercussions throughout the chain and thus other solutions may become more feasible to maximise NPV.

It was somewhat surprising to see the limited effect of the harvest system used in terms of gains. When the system on the whole is operating at peak performance (minimal fibre loss, optimal extraction equipment performance), merchandising yard based merchandising becomes a better choice for increasing value. One of the limitations of this study was that the cost of implementing such a system was not considered. It may be the case that when this cost is taken into account, the small value increase provided may not actually end up being beneficial. Developing the infrastructure of a “new” centralised merchandising location will fall into the ambit of capital costs and the financial depreciation of such does not fall in the more operational costs and revenues associated with this study.

What was also surprising was the lack of clear differences in terms of felling method or skidder type. Grapple skidders are noted for their higher productivity (Ackerman et al. 2014); however, from a cost perspective, it would appear that when a cable skidder functions near optimally, the lower hourly cost puts it in the same tier as a grapple skidder despite the lower productivity. Felling methods also showed no clear advantage when used optimally; a well-run motor-manual operation appears to be equally as good as a mechanical feller-buncher.

It is important to note that this situation applies for current operating costs using these systems. Any changes in terms of costs, be it capital, fuels, maintenance, labour, etc. either increased or decreased will likely change this result. In fact, although not the focus of this study, it is suspected that considering mechanised systems (feller-buncher, grapple skidders) are generally much more expensive to run, any increase in capital or operating costs will likely make these systems less feasible when compared to an optimally run motor-manual system. A change in labour costs could affect motor-manual systems more due to the number of choker-setters (the only additional labour component cost between the two systems). Choker setters are however run on a base-line salary structure and typically not at a highly skilled level meaning that changes in labour costs are unlikely to affect costs significantly. What this study does highlight is that correct skidder utilisation is the most important factor given the current cost climate for these machines and systems.

One limitation of this case study is whether an optimal situation is feasible for a motor-manual, cable skidder extraction system. While fibre losses in these systems are actually lower than the mechanised, grapple skidder systems due to the smaller felling saw kerfs (Ackerman and Pulkki 2012), it may not be possible to reach the proposed reduction in fibre losses. Additionally, greater supervision would likely be required to reach this level of efficiency and this cost was not considered. Furthermore, in order for a system to reach this reduction of fibre losses, it becomes likely that productivity may be decreased. It is possible that once these limitations and costs are factored into consideration, the mechanised felling, grapple skidders again come out on top.

Finally, NPV, while an excellent tool to compare capital opportunities (Bullard and Straka 2011), does not give a final expected revenue figure. As a result, the exact financial benefit of implementing these systems is not known. Although the effect of changing interest rates has been discussed, to understand the exact effect, a sensitivity analysis would have to be performed. This is perhaps a useful avenue for future studies.

Conclusion

The objective of this study was to determine potential gains that can be expected by applying SCM principles through the incremental upgrading of an existing forest road network by manipulating a variety of factors along the value chain over a 30 year period: different timber preparation and primary transport systems, improving efficiencies of both primary and secondary transport and reducing fibre losses along the value chain. The additional silvicultural and management costs incurred over the period were taken into consideration. SCM principles were analysed by investigating the effect of the smaller scale and incremental interventions through the supply chain from forest to mill. Net present value financial analysis was used to determine how these interventions ultimately affect the expected returns to the estate. The study was based on a case study area in the Eastern Cape Province of South Africa.

In order to address all possible combinations of the factors mentioned above, 144 scenarios were created. NPV analysis revealed the best net return achievable to be in the order of R300.8 million with the lowest return being R40.4 million. The best return is associated with a highly upgraded road network and associated fast secondary transport speeds, cable skidder extraction with motor manual felling and cross-cutting at a merchandising yard (all factors at optimal performance). Examination of individual factors found that systems performance, secondary transport speeds and road network had the greatest influence on the final result, with systems performance (and fibre losses in particular), providing the largest impact. Secondary transport speed followed as the second most important factor, as nine of the top ten NPV scenarios were able to achieve the highest possible road design speeds. Higher class networks consistently outperformed the baseline and simplified scenarios.

The study revealed that the harvesting system used had a limited effect in terms of gains. When the system on the whole is operating at peak performance, merchandising yard based merchandising becomes a better choice for increasing value. There was also no clear difference in terms of felling method or skidder type. It would appear that when a cable skidder functions near optimally, the lower hourly cost puts it in the same tier as a grapple skidder despite the lower productivity. Felling methods also showed no clear advantage when used optimally; a well-run motor-manual operation appears to be equally as good as a mechanical feller-buncher.

The study met its objective in illustrating that attention to individual factors within a supply or value chain can add significantly to both financial returns and resource utilisation. However, it is clear that the optimised use of potentially the most productive machine in one system does not provide the best final results for all scenarios, and that it is the basic harmonisation of all factors that must be taken into account. As in all three previous and related studies, the human element plays a large part.

Acknowledgements

The authors would like to thank the following organisations and people for assisting with this project: The South African Forest Industry, the contractors for their data, and University of British Columbia exchange students; Cynthia Lu, Sam Field and Debbi Leung.

References

Ackerman PA, Pulkki RE. 2002. Economic impact of secondary intermediate transport of pulpwood to truck transport depots in South Africa: three case studies. *International Journal of Forest Engineering* 14(2): 53-63.

Ackerman PA, Pulkki RE. 2004. Shorthaul transport of roundwood pulpwood in South Africa: a network analysis case study. *South African Forestry Journal* 201(1): 43-51.

Ackerman PA. 2003. An investigation into shorthaul transport of pulpwood in South Africa. MSc Thesis. Stellenbosch University. South Africa.

Ackerman PA, Pulkki RE. 2012. Fibre volume losses of eight softwood clearfell harvesting systems in South Africa. *Southern Forests: a Journal of Forest Science* 74:2, 133-149. DOI: 10.2989/20702620.2012.701412.

Ackerman PA, Pulkki RE, Gleasure E. 2014. Modelling of wander ratios, travel speeds and productivity of cable and grapple skidders in softwood sawtimber operations in South Africa. *Southern Forests: a Journal of Forest Science* 76(2): 101-110. DOI: 10.2989/20702620.2014.917355.

Ackerman PA, Pulkki RE, Gleasure E. 2015. Softwood sawlog secondary transport travel speed prediction for the South African forestry industry. *Southern Forests: a Journal of Forest Science* 77(2): 107-113. DOI: 10.2989/20702620.2014.984150.

Bullard SH, Straka TJ. 2011. *Basic concepts in forest valuation and investment analysis*. 3rd edition. Jackson, Mississippi: Forestry Suppliers Inc.

Carlsson D, Rönnqvist M. 2005. Supply chain management in forestry – case studies at Södra Cell AB. *European Journal of Operational Research* 163: 589-696.

Dykstra DP. 1984. Mathematical programming for natural resource managers. McGraw-Hill Book Company, New York.

Milton JS, Arnold JC. 1999. *Introduction to probability and statistics: principles and applications for engineering and the computing sciences* (2nd edition). New York: McGraw-Hill.

Forest Economic Services. 2012. Financial analysis and costs of forestry operations MP-South…

Ham, C., Jacobson, M., 2012. Financial decision making in forestry projects. In: South African Forestry Handbook. Southern African Institute for Forestry, pp. 491–500.

Morkel R. 1994. The management of South African forest roads in perspective. BSc(Hons) thesis, University of Stellenbosch, South Africa.

Poirier CC. 1999. *Advanced Supply Chain Management: how to build a sustained competitive advantage*. Berrett-Koehler Publishers Inc. San Francisco. 300 pp.

Pulkki RE. 1984. A Spatial database – heuristic programming system for aiding decision-making in long-distance transport of wood. Acta Forestalia Fennica 188.

Pulkki RE. 1996. Water crossings versus transport costs: A network analysis case study. Journal of Forest Engineering 7:59-64.

Pulkki, R. 2001. Role of supply chain management in the wise use of wood resources. *Southern African Forestry Journal* 191: 89-96.

RSA (Republic of South Africa). 1996. National Road Traffic Act (Act No. 93 of 1996). *Government Gazette, South Africa* 1892(17603).

SANRAL (South African National Roads Agency Limited). 2003. Geometric design guidelines. Available at http://www.nra.co.za/live/click.php?u=%2Fcontent%2FGDGGeometricDesignGuide.pdf&o=Item%2B233&v=814d8c [accessed 3 June 2015]

SANRAL. 2012. South African road classification and access management manual. Technical Report for Highways no. 26. Pretoria: SANRAL.

Statistics South Africa. 2015. PPI History: Final manufactured goods. *P0142.1 – Producer Price Index (PPI), April 2015*.

Taha HA, 1982. Operations research an introduction. Sixth edition. Prentice Hall, New York.

Chapter 7: Summary of papers and significance of the research

The overall objective of this study is to quantify and model potential monetary gains and improved resource utilisation of a typical forest to mill softwood sawlog supply chain in South Africa through incremental optimisation of various stages of the wood procurement process, given the additional silvicultural and management costs, was achieved.

The supply chain analysis case study is based on the outcomes of the three preparatory and related studies in which fibre balance, a terrain factor, primary transport travel speeds and efficiency, as well as secondary transport travel speeds and transport efficiencies in softwood sawlog production and transport systems were examined. Included in this study were the available timber resource, current harvesting systems, and an incrementally improved and upgraded forest road network of the case study area.

A limitation of this study is that only the forest to mill in-feed chain was examined. Although it is believed that the processing industry has an understanding of mill processes, the potential gains that can be achieved by looking across traditional wood procurement boundaries remains as with work done in this study, unstudied at this point in time.

This case study required that the current forest road network be repeatedly refined through road decommissioning and selected road upgrades. Four road scenarios were created. Using a network analysis model and a raster-based Geographic Information System (GIS), the timber resource was flowed over the road networks to the processing plant, taking into account fibre losses (or gains) during each phase of the supply chain. With sequentially improved primary transport efficiency and reduced fibre losses, increased secondary transport travel speeds and transport efficiencies, it was possible to quantify the net financial return of the various projects, production costs and timber resource utilisation. The supply (value) chain was analysed by investigating the effect that downstream systems, as well as efficiency interventions and incremental improvements, would ultimately have on the Net Present Value (NPV) to the estate over one rotation period of 30 years.

NPVs varied radically across the 144 scenarios ranging from approximately R40 million to R300 million. The scenario associated with the highest NPV utilised the most improved road network, highest possible transport speed with the motor-manual felling, cable skidder extraction, merchandising yard, and optimal skidder and transport performance. The lowest NPV yielding scenario is associated with the abridged road network, low transport speed, cable skidder extraction, mechanised felling, roadside merchandising, and normal skidder and transport performance. Examination of the individual factors found that road network, and secondary transport speeds and performance were significant. Harvest system was not significant in terms of the findings within the individual levels of the supply chain. Paper I quantified fibre losses as a percentage of total utilisable volume in softwood sawlog operations country wide. Eight treatments were developed and comprised of felling method (motor-manual or mechanised), average tree class size (less than 1.0 m^3 or greater than or equal to 1.0 m^3) and merchandising location (roadside or at a centralised merchandising yard). Fibre loss categories included stump volume, felling and crosscut saw kerf, log trimming allowance, wood left in-field, and finally the excessive trimming and removal of merchantable wood. Fibre value recovered was determined by using a simulation programme SIMSAW 6 (Wessels *et al.* 2006).

Results show that total fibre losses varied between 6.7 % for mechanised felling, in trees greater or equal to 1 m^3 and compartment roadside merchandised, to 9.9 % for motor-manual felling, in trees less than 1 m^3 and merchandising yard treatment. As far as those losses are concerned, the excessive trimming of merchantable wood amounted to 2.0 % of the total volume loss. It was determined that because log-scalers tend to be over-cautious (or careless) with their decisions surrounding defects, more volume is lost than may be needed

Incorrect log trimming allocation allowance amounted to 0.6 % of the total volume lost. When logs are under-scaled, there is a risk that they will be relegated to a lower length class, and more wood is therefore lost. Overall, trees are felled 7 cm higher than a reasonable felling height. This amounted to a volume loss of 0.8 % of the total volume. Mechanised felling produced lower stumps, but the saw kerf is inordinately large in width at approximately 5.5 cm. It has been found however that the overall benefit of lower stumps despite the increased saw kerf is beneficial (Hall and Han 2006).

In terms of total fibre value and cost and based on the total volume of wood not recovered because of volume losses, the revenue lost is R393 million y^{-1} in board products and R166 million y^{-1} in roundwood supply from plantations.

In Paper II 13 unique operations split between three cable- and two grapple skidders primary transport systems were observed in the Western, Southern and Eastern Cape and KwaZulu-Natal forestry regions of South Africa. A total of 427 complete extraction cycles were timed. Data were collected by a combination of time-studies and remote sensing using a GPS data logger mounted on each machine. Remotely sensed data was used to determine travel distances and speeds for each machine. This information allowed for specific machine productivity calculations. Other data collected per operation were terrain factors which were interpreted into a series of operating risk factors

The examination of skidder wander ratios, travel speeds and loading efficiency found that a constant ratio of 1:1.12 applies across the board over a range of slopes. Skidder speeds varied considerably, but those of the cable skidders and grapple skidders were similar. With regards to in-field measured productivity, grapple skidders were found to be significantly more productive than the cable skidders. On the other hand, it was found that skidder productivity was approximately 50% of potential payload achievable. Overall, improving operational efficiencies and examining appropriate load sizes may be the key to better skidder performance on the long term.

In Paper III softwood sawlog secondary transport operations were studied. Five different, but typical sawlog transport vehicles were remotely tracked over in excess of 43 000 kms. Data was collected using a remote GPS tracking system. Payload data was provided by real-time data capture via vehicle mounted weigh scales. Percentages of maximum legal payloads were used as opposed to actual payload masses; hence 0% indicated an unloaded truck and 100% a fully legally loaded vehicle with higher percentages indicating an overloaded vehicle. Physical road assessments were conducted on the routes surveyed. Segments were identified based on continuous similar surface condition, road width and changes in grade. Surface condition was assessed and a Visual Condition Index (VCI) (Jones and Paige-Green 2000) was calculated for each segment.

With regards to the modelling of secondary transport, the predictor variables included road width and percentage maximum load in both directions of travel. Average road gradient and VCI were not included. It was surprising to see how commonly overloading of trucks occurred with one vehicle found to be overloaded 95% of the time.

Over and above the work in Papers I, II, and III, which are in their own right novel, the study undertaken in Paper IV is unique to the South African forest industry in general and softwood sawlog procurement in particular. The study has shown that it is possible to optimise a supply chain in terms of both monetary value and resource use through understanding the potential interactions between the different components of the supply or value chain.

The findings of this study have far reaching implications for the sawtimber industry in South Africa. It has shown that the current practice of short term or individual lower-level optimisations, on their own, will not lead to improvements of the overall outcomes; an outcome that is unsustainable. One example concerns the application of grapple skidders, known for their high production and low labour component, and seemingly preferred by the sawlog producers not only in South Africa. A cable skidder with its inherently lower operating cost operated at full capacity, with low fibre loss motor-manual felling systems and more efficient secondary transport over good and refined road network to a merchandising yard is of greater value than a grapple skidder system (with mechanised felling) by R5.0 million in net returns and almost 1 000m^3 in additional fibre gained annually. The point here is not so much the skidder type but the efficiencies in and around the system. The same argument applies to the use of motor-manual and mechanised felling systems.

It would nevertheless depend on the situation. If high production is required as in the case of, for example, fire damage or insect attack salvage operations when large volumes need to be processed quickly, high production mechanised systems are needed. But then these are implemented with due recognition of the potential risks of increased overall cost of production and fibre losses. Context surrounding these situations is crucial to making the optimal choice.

Harvesting system selection, harvest planning and the control of operations, albeit outsourced or under company supervision and control, remain important and this revolves around the human factor. In all facets of the value chain researched in this work, the influence of the human element in each phase of the operation is pertinent. In wood procurement harvesting and transport, systems are driven and managed by people, and training, attitudes and levels of supervision will ultimately dictate success or failure. The industry has attempted to subvert the human factor by "mechanising" some levels of the procurement chain with the same if not poorer results as experienced previously. In the process they have ignored the basic principle of close supervision and control, and without intervention the *status quo* will be maintained. An example is the failure of semi-mechanised centralised merchandising yards in South Africa, despite all the potential benefits seen in New Zealand and throughout this study (Ackerman and Pulkki 2012 and Murphy *et al. 2014)*. The high volume input to the yard combined with labour and supervision not orientated into the philosophy of centralised work produced this outcome. The interaction of the human element and the system remain a supply chain question.

Although deliberately ignored by industry, apart from a few companies, a well maintained network of roads of reasonable density and design remains one of the most important aspects in the Supply (value) chain. Unfortunately South African foresters have neglected road maintenance, and inadvertently and through lack of foresight, driven up road densities over time (Ackerman and Pulkki 2003, Ackerman and Pulkki 2004). Poor road surfaces drive down secondary transport speeds, increase vehicle maintenance costs and hence reduce efficiency. High road densities in turn reduce the relative spending per metre road for road maintenance which in turn reduces the effectiveness of the transport function.

A limitation of this study is that only the forest to mill supply chain was analysed. Although it is believed that the processing industry has an understanding of mill processes, the potential gains that can be achieved by looking across traditional wood procurement boundaries remain, as was the work done in this study, unstudied at this point in time. Given the results of NPV analysis, significant benefit to the wood procurement side of the chain can be reached, and potentially, if this boundary between wood procurement and wood processing is crossed, the benefits to the entire chain could increase further.

This gap in knowledge should be rectified through a follow up study. In addition, little research has been done on the effect of overloading on unpaved roads and in particular the costs in terms of damages to the road network are unknown. Further research should focus on further investigating both these areas.

References

Abbas D, Handler R, Dykstra D, Hartsough B, Lautala P. 2013. Cost analysis of forest biomass supply chain logistics. *Journal of Forestry* 111(4): 271-281. DOI: http://dx.doi.org/10.5849/jof.12-054

Ackerman PA, Laengin DW. 2010. Introduction. In: Laengin et al (eds.) South African ground based harvesting handbook. Forest Engineering Southern Africa. ISBN 978-0-620-49065-8. Pp 180.

Ackerman PA, Laengin DW, Olsen G. 2010. Introduction to ground based harvesting systems and methods. In: Laengin et al (eds.) South African ground based harvesting handbook. Forest Engineering Southern Africa. ISBN 978-0-620-49065-8. Pp 180.

Ackerman PA, Pulkki RE. 2003. An investigation into shorthaul transport of pulpwood in South Africa. MSc Thesis. Stellenbosch University. South Africa.

Ackerman PA, Pulkki RE. 2004. Shorthaul transport of roundwood pulpwood in South Africa: a network analysis case study. *South African Forestry Journal* 201(1): 43-51.

Ackerman PA, Pulkki RE. 2012. Fibre volume losses of eight softwood clearfell harvesting systems in South Africa. *Southern Forests: a Journal of Forest Science* 74(2): 133-149.

Ackerman PA, Pulkki RE, Gleasure E. 2014. Modelling of wander ratios, travel speeds and productivity of cable and grapple skidders in softwood sawtimber operations in South Africa. *Southern Forests: a Journal of Forest Science* 76(2): 101-110.

Ackerman PA, Pulkki RE, Gleasure E. 2015. Softwood sawlog secondary transport travel speed prediction for the South African forestry industry. *Southern Forests: a Journal of Forest Science* 77(2): 107-113.

Berg S, Fischbach J, Brüchert F, Poissonnet M, Pizzirani S, Varet A, Sauter UH. 2012. Towards assessing the sustainability of European logging operations. *European Journal of Forest Research* 131: 91-94.

Carle MA, D'Amours S, Gunn E and Pulkki. 2015. Framework for Value Chain Optimzation of Forest Networks in the Emerging Canadian Bioeconomy. NSERC Strategic Network on Value Chain Optimization, Book Chapter accepted for publication. 25pp.

Carlsson D, Rönnqvist M. 2005. Supply chain management in forestry – case studies at Södra Cell AB. *European Journal of Operational Research* 163: 589-616.

Chauhan SS, Frayet JM, LeBel L. 2009. Multi-commodity supply network planning in the forest supply chain. *European Journal of Operational Research* 196: 686-696.

Christopher, M. 1998. *Logistics and Supply Chain Management: Strategies for Reducing Cost and Improving Service*, 2nd edn, Financial Times Management, London. 294 pp.

Conrad IV JI, Bolding MC, Aust WM, Smith RD. 2010. Wood-to-energy expansion, forest ownership changes, and mill closure: Consequences for U.S. South's wood supply chain. *Forest Policy and Economics* 12: 399-406.

Epstein R, Morales R, Serón J, Weintraub A. 1999. Use of OR systems in the Chilean forest industries. *Interfaces* 29: 7-29.

Frayet JM, D'Amours S, Rousseau A, Harvey S, Gaudreault J. 2007. Agent-based supply-chain planning in the forest products industry. *International Journal of Flexible Manufacturing Systems* 19: 358-391.

Frombo F, Miniciardi R, Robba M, Rosso F, Sacile R. 2009. Planning woody biomass logistics for energy production: a strategic decision model. *Biomass and Bioenergy* 33:372-383.

FSA (Forestry South Africa). 2013. Abstract of South African forestry facts for the year 2010/2011. Rivonia: Forestry South Africa.

Gold S, Seuring S. 2011. Supply chain and logistics issues of bio-energy production. *Journal of Cleaner Production* 19: 32-42.

Hall R, Han HS. 2006. Improvements in value recovery through low stump heights: mechanized versus manual felling. *Western Journal of Applied Forestry* 21(1): 33-38.

Jones D, Paige-Green P. 2000. Draft TMH12: Pavement management systems: Standard visual assessment manual for unsealed roads (version 1). Pretoria: CSIR Transportek.

Lawrence R. 2007. Corporate social responsibility, supply-chains and Saami claims: Tracing the political in the Finnish forestry industry. *Geographical Research* 45(2): 167-176.

Lintu, L. 1986. Marketing in the forestry sector. *Unasylva*: 153. Available from: http://www.fao.org/docrep/r9400e/r9400e03.htm#marketing%20in%20the%20forestry%20sector. Accessed 28 March 2014.

Murphy G, Valkenburf R, Ganley D. 2014. Development of an automated system for counting, measuring and tracking export logs arriving on trucks and railway wagons. 5th Forest Engineering Conference. September 23-26. Gerardmer, France.

Poirier CC. 1999. *Advanced Supply Chain Management: how to build a sustained competitive advantage*. Berrett-Koehler Publishers Inc. San Francisco. 300 pp.

Pulkki R. 2001. Role of supply chain management in the wise use of wood resources. *Southern African Forestry Journal* 191: 89-96.

Rotherham, AA. 1999. Supply chain management and the forest industry. *The Forestry Chronicle* 75(3): 361-363.

Stadtler, H, Kilger, C (eds.) 2005, *Supply Chain Management and Advanced Planning: Concepts, Models, Software and Case Studies*, 3rd edn, Springer Berlin, Heidelberg.

Wessels CB, Price CS, Turner P, Dell MP. 2006. Integrating harvesting and sawmill operations using an optimized sawmill production planning system. In: Ackerman PA, Längin DW, Antonides MC (eds), *Precision forestry in plantations, semi-natural and natural forests: proceedings of the International Precision Forestry Symposium, 5-10 March 2006, Stellenbosch University, South Africa.* Stellenbosch University. pp 341-349.

Windisch J, Sikanen L, Rösser D, Gritten D. 2010. Supply chain management applications for forest fuel procurement – cost or benefit? *Silva Fennica* 44(5): 845-858.

Appendix

Declaration by candidate and co-authors

With regard to Chapter 2 (Paper one - Fibre volume losses of eight softwood clearfell harvesting systems in South Africa), the nature and scope of my contribution were as follows:

Nature of contribution	Extent of my contribution (%)
Conceptualised and wrote the paper	90%

The following co-author contributed to Chapter 2:

Name	E-mail address	Nature of contribution	Extent of contribution
RE Pulkki	rpulkki@lakeheadu.ca	Contributed to the writing of the paper	10%

With regard to Chapter 3 (Paper two - Modelling of wander ratios, travel speeds and productivity of cable and grapple skidders in softwood sawtimber operations in South Africa), the nature and scope of my contribution were as follows:

Nature of contribution	Extent of my contribution (%)
Conceptualised and wrote the paper	80%

The following co-author contributed to Chapter 3:

Name	E-mail address	Nature of contribution	Extent of contribution
RE Pulkki	rpulkki@lakeheadu.ca	Contributed to the writing of the paper	5%
E Gleasure	Gleasure @sun.ac.za	Contributed to the writing of the paper	15%

With regard to Chapter 4 (Paper 3 - Softwood sawlog secondary transport travel speed prediction for the South African forestry industry), the nature and scope of my contribution were as follows:

Nature of contribution	Extent of my contribution (%)
Conceptualised and wrote the paper	80%

The following co-author contributed to Chapter 4:

Name	E-mail address	Nature of contribution	Extent of contribution

RE Pulkki	rpulkki@lakeheadu.ca	Contributed to the writing of the paper	5%
E Gleasure	Gleasure @sun.ac.za	Contributed to the writing of the paper	15%

With regard to Chapter 5 (Paper 4 - An Eastern Cape Softwood Sawtimber Supply Chain Case Study), the nature and scope of my contribution were as follows:

Nature of contribution	Extent of my contribution (%)
Conceptualised and wrote the paper	80%

The following co-author contributed to Chapter 5:

Name	E-mail address	Nature of contribution	Extent of contribution
RE Pulkki	rpulkki@lakeheadu.ca	Contributed to the writing of the paper	5%
E Gleasure	Gleasure @sun.ac.za	Contributed to the writing of the paper	15%